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Performative Microforests

Investigating the potential benefits of integrating spatial vegetation environments into buildings, in regards to the performance of buildings, their occupants + local ecosystems

Giancarlo Mangone

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“Imagination is more important than knowledge. Knowledge without imagination is barren”
Albert Einstein

“The only way of finding the limits of the possible is by going beyond them into the impossible”
Arthur C. Clarke

“It’s always been the artist who perceives the alterations in man caused by a new medium, who recognizes that the future is the present, and uses his work to prepare the ground for it”
Marshall McLuhan

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TOC

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Summary

The design of office buildings can substantially improve the building, social, and ecological performance of office building projects. However, existing research on improving the performance of work environments has primarily focused on identifying and evaluating methods to make work environments less bad, rather than focusing on how to develop work environments that are positively performing.[114, 256,261, 313, 468, 485] Moreover, the potential of building projects to perform positively, in terms of economic, social, and ecological performance, remains relatively unexplored in existing research and building projects. To this end, this PhD research project is focused on exploring the positive economic, social, and ecological performance potential of buildings. Specifically, this research project identifies and evaluates the potential economic, social, and ecological performance benefits of integrating microforests into office buildings.

Microforests are defined in this book as dynamic, stimulating, cohesive spatial environments that are composed of vegetation and soil layers that mimic the structural, perceptual, and ecological composition of a forest ecosystem, yet are not large enough to reliably provide the myriad of functions of a robust, mature forest ecosystem. This design research focus is based on findings from existing literature that suggest that natural environments and stimuli can provide a diverse range of economic, social, and ecological performance benefits.[95, 199,204, 288, 327, 329, 339, 388, 442, 472, 487]

The Design Research Methodology [DRM], an established research methodology that facilitates the use of diverse research methods in a rigorous, effective manner,[51, 315] is used in this research project to explore and evaluate the performance potential of microforests, by investigating the following sub research questions :

- ***How can microforests improve the performance of office buildings?***
- ***How can microforests improve employee performance + comfort?***
- ***How can microforests improve the ecological performance of office buildings?***

Within the DRM research framework, explorative design case studies, systematic literature reviews, expert interviews, observation case studies, and experimentation research methods were employed, in order to develop design guidelines, high performance space types and case studies, as well as assessments of the hypotheses of several experiments.

For instance, as part of the investigation of the first sub research question, a design case study was conducted that evaluated the potential of microforests to reduce the energy consumption rates of office buildings, both in terms of the potential of vegetation to function as a shading device, and in terms of the potential energy savings that can be attained through the provision of semi-outdoor, high quality microforest workspaces. The results of this study, which are discussed in Chapter 4, indicate that vegetation can be as effective, or more effective, than typical shading devices, in terms of shading effectiveness. Moreover, in terms of economic performance, this study found that improving occupant work performance provided substantially greater economic benefits than reducing the energy costs of the mid-size commercial office building. This finding indicates that, in terms of economic performance, design teams should be focused on designing office environments that improve worker performance. Thus, the results of this case study indicate that economic and worker performance are interrelated.

In order to investigate the potential effects of microforests on occupant thermal comfort, a quasi-experiment which evaluated the potential psychological and physiological impacts of microforests on occupant thermal comfort, was conducted. This study is discussed in Chapter 5. The results of this study indicate that working within a densely vegetated work environment, such as a microforest, improves occupant thermal comfort, both in normal and more extreme temperatures, throughout the four seasons. Thus, the inhabitation of microforests can improve occupant thermal comfort, as well as reduce building energy consumption rates, by allowing the temperature set point of the space to be raised in the summer and lowered in the winter.

In terms of microforests impacting worker performance, a multidisciplinary, systematic literature review was conducted to identify the potential of the design of work environments to impact worker performance, particularly natural environments such as microforests. The results of this review, which are discussed in Chapter 6, indicate that natural environments can provide a diverse range of worker performance benefits. However, further research is necessary to determine the effectiveness of various design solutions, space types, and space qualities on worker performance. To this end, a survey was conducted to evaluate the types of work environments and space qualities that promote worker performance, including constructed and natural environments, in terms of a diverse range of work tasks. The results of this study, which are described in Chapter 7, suggest that knowledge workers prefer to conduct a wider variety of work tasks in microforests, compared to a range of existing work space types, than existing research suggests. Moreover, the results of this study suggest that different types of microforests, such as spatially open and public microforests compared to more dense and private microforests, provide different performance benefits, and are preferred for different work tasks. Hence, these findings suggest that the integration of microforests into office buildings can improve worker performance, and from a more general perspective, that workers prefer to have access to more diverse types of work spaces within their office environment than typical office environments provide. Furthermore, the results of the conducted studies indicate that the design of work space environments, at both the scale of individual spaces and space qualities, impacts worker performance, and thereby should be accounted for in the design of office environments.

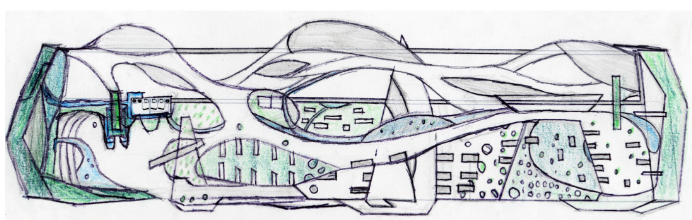
In terms of microforests impacting the ecological performance of building projects, a systematic literature review was conducted to investigate the ecological performance potential of building projects. The results of this review are presented in Chapters 8-11. Three general design strategies to improve the ecological integrity of local ecosystems were identified : design for ecosystem functions, design for ecological behavior, and design for biodiversity. The potential effectiveness of various design strategies within these three general design strategies were explored, as well as gaps in existing research, and issues with evaluating the ecological performance of building projects. Potentially effective design solutions were identified, such as hybrid infrastructure, gene seed banks, and constructed environments which are designed to foster positive experiences in natural environments. Moreover, the results of this review indicate that further research is needed to evaluate the comparative value of different ecological design solutions, as well as effective means to account for the interrelationships of building projects with their local and regional contexts.

Taken together, the results of this research project make it evident that the design of constructed environments has a significant impact on the performance and value of building projects, from economic, social, and ecological performance perspectives. More specifically, the integration of microforests into office environments was found to yield a diverse range of building, worker, and ecological performance benefits.

The results of this research project can aid in the development of comprehensive design support systems and building project performance metric systems, as well as identify, and in some cases evaluate, potentially high performing, innovative design solutions and strategies.

However, it is important to note that the results of this research project indicate that, in order to develop comprehensive building performance evaluation metric systems and design methods, further research is necessary. To this end, this research project identified innovative performance benefits that the design of building projects, and microforests, can provide, as well as identified existing research gaps that should be addressed. This research project also identified potentially high performing space types and design strategies, including various types of microforests.

In summary, the results of this research project demonstrate that the design of building projects can be an effective and efficient method to generate diverse economic, social, and ecological performance benefits. Moreover, the results of this research project suggest that the design of high quality spaces, particularly microforests, can improve the social and ecological performance of building projects, while at the same time, also reduce building costs.



Conceptual plan of microforest integrated office environment

Samenvatting

Het ontwerp van kantoorgebouwen kan substantieel bijdragen aan het verbeteren van de bouwkundige, sociale en ecologische prestaties van dergelijke bouwprojecten. Bestaand onderzoek met betrekking tot de verbetering van werkomgevingen is eerder gericht op het identificeren en evalueren van methodes om werkomgevingen minder slecht te maken dan op het ontwikkelen van werkomgevingen die een positieve bijdrage leveren.[14, 256,261, 313, 468, 485] Bovendien blijft in bestaand onderzoek en gedurende bouwprojecten de potentie van bouwprojecten om positief bij te dragen aan de economische, sociale en ecologische prestaties relatief onderbelicht. Dit promotieonderzoek is daarom gericht op de mogelijke positieve economische, sociale en ecologische prestaties van gebouwen. Meer specifiek richt dit onderzoeksproject zich op het identificeren en evalueren van potentiële economische, sociale en ecologische prestatievoordelen van het integreren van 'microforests' (letterlijk: microbossen) in kantoorgebouwen.

Microforests worden in dit boek gedefinieerd als dynamische, stimulerende, samenhangende ruimtelijke omgevingen die worden gevormd door vegetatie en bodemlagen die de structuur, perceptieve en ecologische samenstelling van een bos-ecosysteem nabootsen, maar die niet groot genoeg zijn om betrouwbaar de ontelbare functies van een robuust volwassen bos-ecosysteem te kunnen leveren. Dit ontwerpend onderzoek is gebaseerd op bevindingen uit bestaande literatuur die suggereert dat natuurlijke omgevingen en natuurlijke stimuli tot een een breed scala aan economische, sociale en ecologische prestatievoordelen kunnen leiden.[95, 199,204, 288, 327, 329, 339, 388, 442, 472, 487]

De 'Design Research Methodology' (DRM), een gerenommeerde onderzoeksmethodologie die het gebruik van verschillende onderzoeksmethoden op een effectieve manier faciliteert,[51, 315] wordt in dit onderzoeksproject gebruikt om de prestatiepotentie van microforests te onderzoeken door de volgende onderzoeksvragen te beantwoorden:

- ***Hoe kunnen microforests de prestaties van kantoorgebouwen verbeteren?***
- ***Hoe kunnen microforests werknemerprestaties en comfortcondities verbeteren?***
- ***Hoe kunnen microforests de ecologische prestaties van kantoorgebouwen verbeteren?***

Binnen het DRM onderzoekskader zijn exploratieve ontwerpcasestudies, systematisch literatuuronderzoek, expertinterviews, observatie van casestudies en experimentele onderzoeksmethoden gebruikt, om ontwerprichtlijnen, goed presterende ruimtetypologieën en casestudies te ontwikkelen, alsmede de hypotheses rond diverse experimenten te beoordelen.

Als onderdeel van het onderzoek naar de eerste onderzoeksvraag is bijvoorbeeld een ontwerpcasestudie uitgevoerd naar de potentie van microforests om het energiegebruik van kantoorgebouwen te reduceren, zowel wat betreft de potentie van de vegetatie om als zonwering te fungeren als de potentiele energiebesparing die kan worden gerealiseerd door het bieden van semi-buiten microforestwerkplekken van hoge kwaliteit. De resultaten van deze studie, die in hoofdstuk 4 worden besproken, geven aan dat vegetatie als zonwering even effectief, zo niet effectiever is dan traditionele zonwering. Bovendien gaf deze studie aan dat de verbetering van de prestatie van werknemers substantieel grotere economische voordelen met zich mee bracht dan de verminderde energiekosten voor een middelgroot commercieel kantoorgebouw. Deze bevindingen geven aan dat, met betrekking tot economische prestaties, ontwerpteams gericht zouden moeten zijn op het ontwerp van kantooromgevingen die de prestaties van werknemers bevorderen. Uit deze casestudie blijkt aldus de verwevenheid van economische- en werknemersprestaties.

Om het potentiële effect van microforests op het thermisch comfort van gebruikers te onderzoeken is een quasi-experiment uitgevoerd die de potentiële psychologische en fysiologische invloeden van microforests evalueert. Deze studie wordt besproken in hoofdstuk 5. De resultaten van deze studie geven aan dat het werken in werkomgevingen met intensieve vegetatie, zoals microforests, het thermisch comfort van gebruikers door alle vier seizoenen verbetert, zowel in normale als meer extreme temperatuuromstandigheden. Op deze wijze kan het gebruik van microforests het thermisch comfort van gebruikers verbeteren en tegelijkertijd het energiegebruik van het gebouw verminderen, doordat de insteltemperatuur in de zomer kan worden verhoogd en in de winter verlaagd.

Ten aanzien van de invloed van microforests op de prestaties van werknemers is een multidisciplinaire, systematische literatuurstudie uitgevoerd om de potentie van het ontwerp van werkomgevingen, met name natuurlijke omgevingen zoals microforests, qua invloed op de prestaties van werknemers te bepalen. De resultaten van deze studie, die in hoofdstuk 6 besproken worden, geven aan dat een breed scala aan voordelen ten aanzien van werknemerprestaties kan worden bereikt. Er is echter meer onderzoek nodig om de effectiviteit van verschillende ontwerpoplossingen, ruimtetypologieën en ruimtelijke kwaliteiten te bepalen. Hiertoe is een enquête uitgevoerd, om types van werkomgevingen en ruimtelijke kwaliteiten te evalueren die voor een serie werktaken de prestaties van werknemers bevorderen, inclusief gebouwde en natuurlijke omgevingen. De resultaten van deze studie, beschreven in hoofdstuk 7, suggereren dat, in vergelijking met een reeks bestaande werkplektypen, kenniswerkers een bredere variëteit aan werktaken in microforests verkiezen dan bestaand onderzoek veronderstelt. Bovendien suggereren de resultaten van deze studie dat verschillende typen microforests, zoals ruimtelijk open en publieke microforests, in vergelijking met dichter begroeide en besloten microforests, verschillende prestatievoordelen bieden en voor verschillende werktaken worden geprefereerd. Vandaar dat deze bevindingen suggereren dat de integratie van microforests in kantoorgebouwen de prestaties van werknemers kan bevorderen en, vanuit een meer generiek standpunt, dat werknemers toegang tot meer verschillende types aan werkruimtes binnen hun kantoor omgeving verkiezen dan waar typische kantooromgevingen in voorzien. Verder laten de resultaten van de uitgevoerde studies zien dat het ontwerp van werkomgevingen, zowel ten aanzien van individualiteit als ruimtelijke kwaliteit, de prestaties van werknemers beïnvloeden en dat er, bij het ontwerp van kantooromgevingen, rekening mee gehouden zou moeten worden.

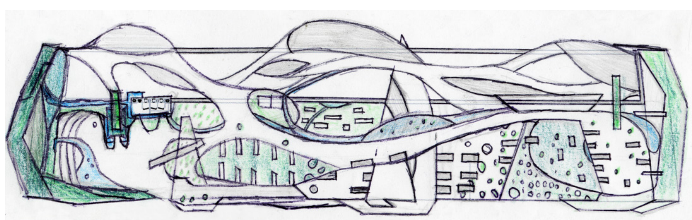
Ten aanzien van de invloed van microforests op de ecologische prestatie van bouwprojecten is een systematische literatuurstudie uitgevoerd om de ecologische prestatiepotentie van bouwprojecten te onderzoeken. De resultaten van dit onderzoek worden gepresenteerd in de hoofdstukken 8-11. Drie generieke ontwerpstrategieën om de ecologische integriteit van lokale ecosystemen te bevorderen werden geïdentificeerd: ontwerpen voor ecosysteemfuncties, ontwerpen voor ecologisch gedrag en ontwerpen voor biodiversiteit. De potentiële effectiviteit van de verschillende ontwerpstrategieën binnen deze drie generieke ontwerpstrategieën zijn onderzocht zowel als lacunes in bestaand onderzoek en problemen ten aanzien van het bepalen van de ecologische prestaties van bouwprojecten. Potentieel effectieve ontwerpoplossingen werden geïdentificeerd, zoals hybride infrastructuur, genetische zaadbanken en gebouwde omgevingen die ontworpen zijn om positieve ervaringen in natuurlijke omgevingen te bevorderen. Verder geven de resultaten in dit overzicht aan dat nader onderzoek nodig is om de vergelijkende waarden van verschillende ecologische ontwerpoplossingen te kunnen bepalen, evenals effectieve methoden om de verbanden van bouwprojecten met hun lokale en regionale contexten in kaart te brengen.

In zijn totaliteit laten de resultaten van dit onderzoek zien dat het ontwerp van gebouwde omgevingen een significante invloed heeft op de prestaties en waarden van bouwprojecten, zowel in economisch, sociaal als ecologisch perspectief. Meer specifiek blijkt de integratie van microforests in kantooromgevingen een breed scala aan voordelen te bieden, zowel ten aanzien van het gebouw, de werknemers, als de ecologische prestaties.

De resultaten van dit onderzoek kunnen helpen bij de ontwikkeling van uitgebreide ontwerpondersteunende systemen en van beoordelingssystemen voor de prestaties van bouwprojecten, evenals bij het identificeren en in sommige gevallen evalueren van potentieel goed presterende innovatieve ontwerpoplossingen en strategieën.

Het is echter belangrijk dat de resultaten van dit onderzoek aangeven dat, om alomvattende gebouwprestatiebeoordelingssystemen en ontwerpmethoden te kunnen ontwikkelen, nader onderzoek nodig is. Dit onderzoek heeft hiertoe innovatieve prestatievoordelen geïdentificeerd die het ontwerp van bouwprojecten en microforests kunnen bieden, evenals bestaande onderzoekslacunes geïdentificeerd die zouden moeten worden ingevuld. Dit onderzoeksproject heeft eveneens goed presterende ruimtetypologieën en ontwerpstrategieën geïdentificeerd, inclusief verschillende types microforest.

Samenvattend tonen de resultaten van dit onderzoek aan dat het ontwerp van bouwprojecten een effectieve en efficiënte manier kan blijken om economische, sociale en ecologische prestatievoordelen te behalen. Bovendien suggereren de resultaten van dit onderzoek dat het ontwerp van kwalitatieve ruimtes, met name microforests, de sociale en ecologische prestaties van bouwprojecten kunnen verhogen en tegelijkertijd de bouwkosten kunnen verlagen.



Conceptueel schema van een kantoorgebouw geïntegreerd microforest

1 Introduction

§ 1.1 Identifying the potential of performance based design

An altered version of a segment of the following subsection was previously published in:
Giancarlo Mangone, Peter Luscuere "*Microforest HVAC: Investigating the performance potential of quality based climate systems*" TVVL Magazine, The Netherlands. June 2013

There is substantial potential for the design of work environments to positively impact the work performance and well-being of their occupants, as well as the performance of buildings, building systems, and local ecosystems. However, if the provision of a neutral performing work environment, defined in this book as a work environment that does not generate discomfort or positively or negatively affect the well-being and worker performance of the occupants, nor positively or negatively affect the ecological integrity of local ecosystems, is considered to be the performance baseline for work environments, than existing research demonstrates that typical work environments reduce employee productivity, creativity, well-being, and comfort. For instance, environments with static temperatures increase stress, reduce the ability of individuals to thermoregulate themselves to maintain thermal comfort, and reduce their thermal comfort range.[485] In addition, typical privacy, noise, personalization, and workspace environment quality issues inhibit employee performance, well-being, and comfort.[114, 254-256, 261, 322, 387, 468] Since workforce related costs account for over 80% of the annual costs of a typical office building,[58] these negative effects of poorly functioning work environments translate into substantial financial losses to companies every year.

To make matters worse, the majority of extant research on the effects of work environments on building and worker performance have generally been focused on making work environments perform less bad, instead of focusing on how to develop work environments that are positively performing. For example, existing research on the effects of the design of buildings and individual spaces on building and worker performance is mainly focused on how to reduce 'bad' behavior and negatively performing environment characteristics, such as reducing noise disturbances, quantities of artificial light, and thermal discomfort, as well as encouraging people to reduce their plug loads.[114, 143, 188, 204, 224, 255, 256, 261, 282, 304, 305, 409, 468] Moreover, the performance of work environments tend to be evaluated based on the quantity of the negative work environment attributes present.[114, 490] In contrast, relatively little research has investigated how to design work environments that promote creativity.[128, 129, 254, 273] However, fixing negative performing characteristics can, at best, result in a neutral performing work environment – the work environment doesn't reduce building and worker performance, but it doesn't improve it either.

Given the current situation, how can positive building environments be developed? The evolutionary development of humans may provide some insight into this problem. Humans have evolved through interactions with sensually stimulating natural environments and processes for millions of years. Research in various scientific disciplines, such as environmental psychology and neuroplasticity, have determined that these interactions with the inherent dynamic and sensually stimulating character of natural environments required adaptive human responses, and were essential to the evolution of humanity's physical, emotional, problem solving, critical thinking, and constructive abilities that are fundamental to human health, maturation, and productivity.[48, 241, 246, 296] In contrast, typical and 'new' office workspace environments usually are not designed to dynamically interact with, stimulate the senses of, or require adaptive responses from, building occupants.[127] For instance, walking through a typical non-sensually stimulating, non-interactive, and non-spatially and sensually dynamic hallway does not engage the indirect attention of occupants, nor does it require the occupants to strategize how to move from one location to another, determine how to orient themselves, or observe or interact with their environment.[49, 164, 241, 279, 439] These types of low quality spatial interactions promote occupants to develop habitual, non-stimulating, non-cognitively demanding, almost mechanical ways of moving through and occupying their office environments. Hence, the occupation of these types of non-stimulating and non-interactive work environments are essentially 'dumbing down' occupants, as well as inhibiting the restoration of the direct attention of occupants, among other negative effects, compared to inhabiting dynamic, interactive environments that promote cognitive, emotional, and physical development, such as natural ecosystems.[48, 49, 164]

Moreover, direct interactions of occupants with elements of local natural environments, which inherently provide a number of benefits to people, [23, 33, 46, 47, 48, 49, 112, 199, 204, 240, 241, 274, 288, 292, 293, 295, 300, 327, 329, 339, 352, 353, 360, 371, 418, 420, 429, 440, 442, 457, 462, 472, 487] used to be a normal living condition, before humans transitioned to spending most of their time within buildings.[447] Now access to these conditions is commonly considered to be a privilege, and in many cases, an unnecessary expense. For instance, access to daylight used to be a standard living condition, not an amenity. Thus, the natural environments humans used to inhabit positively contributed to their performance and well-being, while current work environments typically do not. So how can positively performing work environments be developed in the current era?

The performance potential of high quality, positively performing work environments, and the identification of the characteristics of these types of work environments, remain largely undefined. For example, there are relatively few work environment spatial qualities that have been determined to improve creativity, such as the presence of plants.[129, 273, 339] Furthermore, the interrelationships of positively performing characteristics remain poorly understood, as discussed in Chapters 6 and 7. Nevertheless, there is a growing body of research that is focused on identifying the positive potential of work environments, which is discussed in more detail in Chapter 6. In addition, a number of research findings indicate that the provision of positive performing features in work environments, such as natural environments, may have a larger influence on worker performance, comfort, well-being, and satisfaction than the reduction of negative work environment characteristics. Moreover, the development of positive features in work environments may reduce the importance and influence of negative work environment parameters on building occupants, such as the positive effects of plants on occupant thermal comfort that were found in the study that is presented in Chapter 7.[204, 293] Thus, positive work environments may be more effective, both in terms of improving worker performance, as well as in terms of making negative features more manageable and less influential on worker performance, comfort, and satisfaction.

§ 1.2 Identifying the general focus of the research project

To this end, this PhD research project, which was developed at the Architecture Engineering and Technology Department at the Faculty of Architecture and the Built Environment at Delft University of Technology, was focused on identifying and evaluating the potential of positive performing work environments to improve *building performance* (energy use, operating costs, space efficiency, etc), *worker performance* (occupant creativity, productivity, and well-being), and *ecological performance* (effects of buildings on local ecosystems). Specifically, this research project was focused on identifying and evaluating the potential of a specific workspace type that existing research indicated could be particularly high performing, and high quality: *microforests*. Thus, this research project explored the potential of *microforests* to function as positive performing work environments. As discussed in greater detail in Chapter 2, microforests are dynamic, stimulating, cohesive spatial environments that are composed of vegetation and soil layers that mimic the structural, perceptual, and ecological composition of a forest ecosystem, *yet are not large enough to reliably provide the myriad of functions of a robust, mature forest ecosystem*.

§ 1.3 Problem statement

The potential building, worker, and ecological performance benefits of integrating spatial vegetation design solutions, such as gardens and microforests, into office buildings have not yet been thoroughly explored or evaluated.

§ 1.4 Research objective

The objective of this research project was to identify and evaluate the potential building, worker, and ecological performance benefits of integrating natural environments, in the form of microforests, into office buildings.

§ 1.5 Research questions

In order to effectively address the objective of this research project, potential solutions to the primary research question need to be explored and evaluated through rigorous investigations of a number of sub-questions. The research methods that were employed to investigate the research questions are discussed in Section 1.6.

§ 1.5.1 Primary research question

Can microforests enhance the performance, and promote the occupation, of office buildings?

§ 1.5.2 Sub research questions

1 ***How can microforests improve the performance of office buildings?***
1.1 *How can microforests reduce operating costs?*
1.1.1 *How can microforests reduce energy costs?*
1.1.2 *How can microforests reduce building maintenance costs?*
1.1.3 *How can microforests reduce employee related costs?*

1.2 *How can microforests improve the performance of building systems?*

1.3 *How can microforests reduce construction costs?*
1.3.1 *How can microforests be more cost effective than existing interior vegetation strategies?*
1.3.2 *How can microforests provide high performance multi-task workspaces?*

2 ***How can microforests improve employee performance + comfort?***
The potential of the design of work environments to influence occupant performance and well-being is not yet well understood. Thus, in order to determine the potential of microforests to improve the performance and comfort of building occupants, the following background question must first be investigated:

2.1 *How can the design of office environments influence occupant performance and well-being?*
After investigating this background question, the following sub-questions can be explored.

2.2 *What types of constructed + natural workspace types, and spatial qualities, improve worker performance?*

2.3 *Does the occupation of microforests influence occupant thermal comfort?*

3 ***How can microforests improve the ecological performance of office buildings?***
Similar to the lack of existing research on effective strategies for the design of workspace environments to improve worker performance, the potential of buildings to improve the ecological integrity of local ecosystems is not yet well understood. Therefore, this research project explored the following background questions, in order to determine the potential of microforests to contribute to the ecological integrity of local ecosystems.

3.1 *What is the potential of buildings to improve the ecological integrity of local ecosystems?*
3.1.1 *What is the potential of buildings to improve the ecological functions of local ecosystems?*
3.1.2 *What is the potential of buildings to improve the ecological behavior of occupants?*
3.1.3 *What is the potential of buildings to improve the biodiversity of local ecosystems?*

4 ***Can microforests be designed in a way that effectively addresses multiple performance goals simultaneously?***

4.1 *What are the symbiotic interrelationships between the diverse performance parameters explored in this research project?*

§ 1.6 Approach and methodology

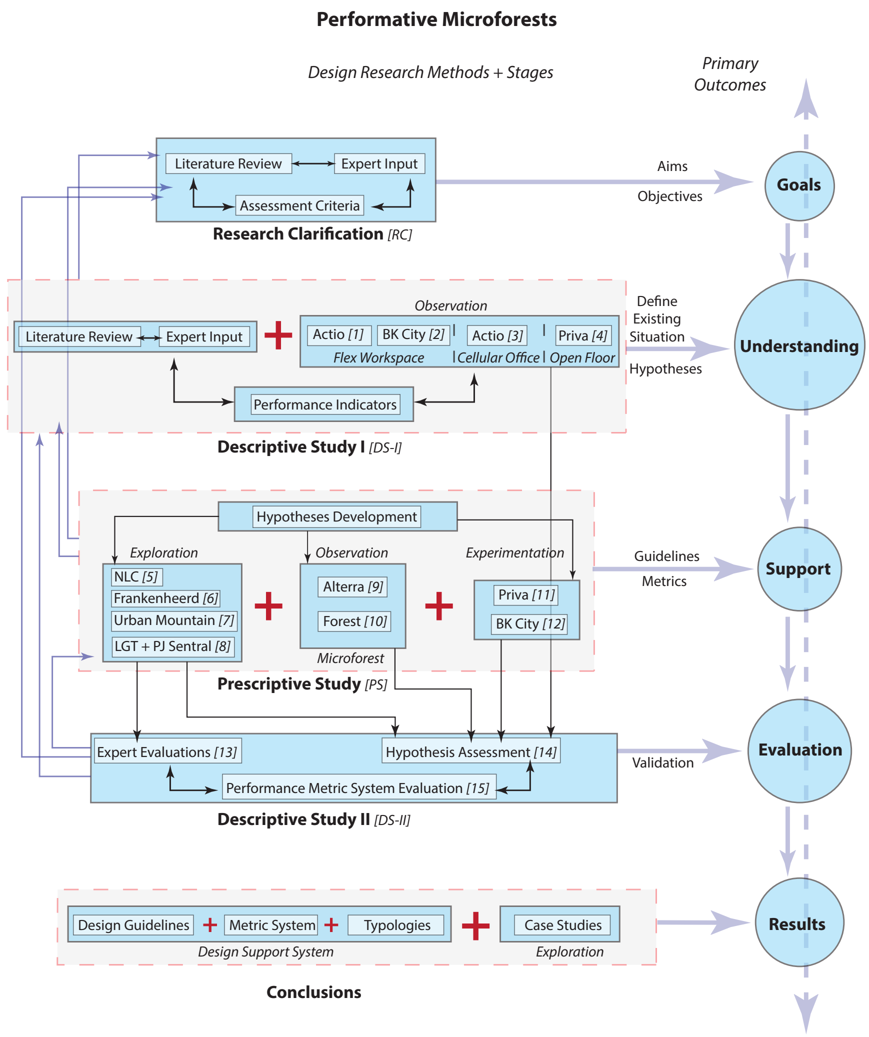


FIGURE 1.1 Performative microforest research methodology

§ 1.6.1 General research approach and methodology

This research project was focused on the development of microforests as individual office spaces within mid-size commercial office building environments. The majority of the research was focused on projects within the context of Central Europe.

This research project was developed from a performance based design perspective. Within this context, the development and evaluation of microforests was based on their potential to improve worker performance, building performance, and ecological performance.

§ 1.6.2 Specific application method of Design Research Methodology (DRM)

The performance potential of microforests was explored and evaluated through the utilization of the Design Research Methodology framework, in order to ensure the scientific significance and quality of the research. DRM is composed of four research phases: Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II. The depth of development of the individual phases depends upon the research project's scope, focus, and resources. For PhD research projects, detailed depth is suggested for one, potentially two phases, as even two detailed phases begins to eclipse the scope of a PhD researcher, due to typical time and research constraints.[51, 315]

It is important to note that the dynamic nature of the DRM methodology allows for diverse research methods and questions to be incorporated into a focused, rigorous research framework. Furthermore, the development of diverse research methods, such as various exploration, observation, and experimentation methods, can provide a diverse array of benefits to the development and execution of research projects. For instance, the use of multiple research methods inherently encourages and generates diverse perspectives to consider research questions, results, and opportunities, as well as diverse validation and observation methods, thereby improving the validity of the research findings, as well as the scope of research projects. In addition, specifically in terms of research in the field of architecture, DRM provides a research method that fosters the rigorous development of design solutions and design processes in ways that provide valid, and otherwise unconsidered possibilities, solutions, and questions.

For instance, through the development of this research project, it became readily apparent that the use of various architectural design processes as research methods identified innovative research questions and opportunities, as well as generated opportunities for validating results found in existing literature, particularly those that were unable to be evaluated through statistical and other more traditional quantitative analysis approaches. Moreover, the incorporation of design processes into this research project allowed for the application of results found in existing literature in ways that allowed for unique explorations and comprehension of the potential ramifications and application potential of existing research. In addition, this design research process resulted in the identification of existing research gaps, and the determination of the relative importance of various possible research projects, questions, and areas, in regards to their applicability to the resolution of specific research questions. Thus, DRM research methodologies are particularly relevant to design related research, but also are important to consider for research projects in other research domains, particularly those that are interdisciplinary in nature.

Research clarification phase

The research clarification (RC) phase is the stage in which researchers search for evidence, or at a minimum, indications, which support their assumptions, in order to identify and develop realistic and high quality research aims and objectives. This phase is typically comprised of literature review.[51] For this research project, expert input was also included as a research component. The results of this phase are a preliminary description of the existing situation, as well as a preliminary description of the desired situation, in order to clarify the assumptions underlying each description. The identification of performance assessment criteria that can be used as measures to evaluate the outcome of the research should also be developed.[51] In the case of this research project, the evaluation criteria were focused on worker performance, ecological performance, and building performance. Thus, the RC phase should result in the development of clear goals and focus for the research project.

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Descriptive study I phase

The purpose of the Descriptive Study I (DS-I) phase is to foster a deeper comprehension of the existing situation, to the point that the performance parameters that should be addressed in the research project to maximize the efficiency and effectiveness of the project are identified. Thus, research methods in this phase should be focused on developing a greater understanding of the existing situation through the identification of the relative value of previously unconsidered performance parameters that the research process up to this point suggests may also be important to consider, as well as through the development of greater insight on the relative value of previously identified performance parameters, in regards to the research questions of the project.[51] It is important to note that this process will also generate a deeper comprehension of the research questions and objectives, and by doing so, can result in the alteration of the project's research questions, objectives, and methods.

Although it is common for research projects to only conduct a literature review in this phase,[51, 315] it is important to note that other research methods, such as expert input and observations, can also provide valuable feedback and insight. For instance, observation case studies can be conducted at this phase to identify *what* performance parameters have an influence on the performance of the existing and desired situation, as well as the degree of influence of various performance parameters. These types of analytical research processes also help determine which performance parameters are important to consider to attain the research objectives. Furthermore, this research phase should also identify and explore *how* these performance parameters can have an influence on the existing and desired situation, as well as the research objectives.

As illustrated in Figure 1.1, the observation case studies (1-4) for this research project were conducted in the Actio office building in Wageningen, The Netherlands (1,3), the research offices within the BK City academic building in Delft, The Netherlands (2), as well as the Priva office building in De Lier, The Netherlands (3). These case studies were focused on observing the worker and building performance of existing workspaces, as illustrated in Figure 1.2 (sub research questions 1-2). Although there are numerous existing workspace types for knowledge workers, such as cellular offices, informal meeting spaces, and open floor workspaces, there is evidence that more flexible work environments, which provide diverse types of work environments for building occupants, result in greater work performance and comfort, as discussed in Chapters 6 and 7.[114, 382] Thus, the Actio and BK City office environments were chosen as suitable case studies because they were both 'flexible' office environments that offer diverse types of workspaces. Furthermore, the Actio building also contained more traditional cellular offices in one floor of the building, which allowed for the comparison of occupants of cellular office workspaces to occupants of flexible office workspaces, within the same building and between workers of similar job types. Moreover, it is interesting to note that the Actio building contained a living wall in the atrium, which allowed for observations of the effects of a non-interactive, interior natural 'surface' on building and worker performance. In contrast, the Priva office building was comprised of open floor workspaces and formal meeting rooms, as described in Chapter 5. This case study allowed for the observation of the effects of common open floor workspace environments on workers and building systems.

Hence, this range of case studies allowed for the evaluation of the effects of various workspace types on the performance of the occupants and the building. For instance, occupant feedback and observation, as well as interviews with the facility managers, were utilized to evaluate the performance of these spaces, the potential for integrating microforests, and potentially identify high and low performing parameters. Moreover, the observation of diverse workspace types and buildings allowed for effective, comparative analysis and comprehension of the performance of various workspace types.

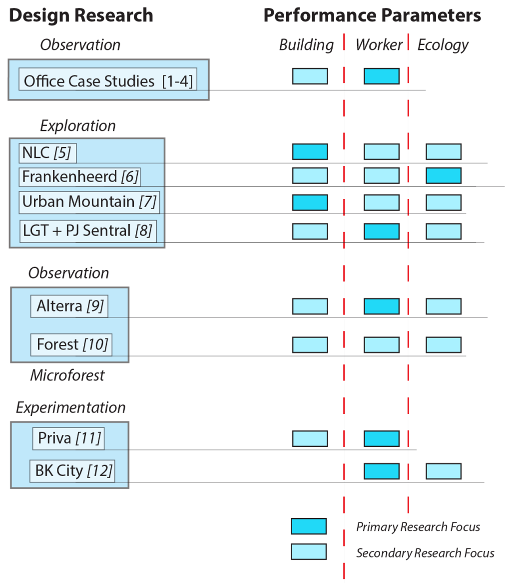

FIGURE 1.2 Performance parameter focus of research studies

Prescriptive study phase

The Prescriptive Study (PS) phase is focused on determining the types and degrees of alterations that need to be made to the existing situation to generate the desired situation. Moreover, now that the existing situation is more comprehensively understood, the definition of the desired situation can be more refined, and in some cases, corrected, both at the beginning and throughout this phase.[51]

Thus, the prescriptive study phase is explorative, in that researchers can test different types and methods of alterations to the existing situation, in order to determine the relative effectiveness of various alteration strategies and solutions, in terms of achieving the desired situation. For instance, the value of a myriad of diverse possible solutions can be determined by evaluating the results of combining different sets of the previously identified influential performance parameters. Furthermore, any existing assumptions, research, and experience the research team has previously developed about how to improve the existing situation, as well as the research team's now increased understanding of the existing and desired situations, as well as their understanding of the potential and inherent interrelationships of the various performance parameters, should be incorporated into the development of the explorations conducted in this research phase. In addition, it is important to note that conducting diverse research explorations at this phase will increase the validity of the outcomes of the research project, by evaluating the potential interrelationships and relative value of various performance parameters and alteration strategies and solutions.

Specifically for this research project, exploration case studies, observation case studies of existing spatial vegetated environments, and experiments were conducted. For instance, the exploratory design case studies [5-8] were developed with building developers, architects, mechanical engineers, horticulturists, psychologists, and experts in several other research domains, during the initial design process of both new construction and renovation projects. These case studies were intended to explore the performance potential of microforests, at the same scale and program as the experiments. By developing exploratory investigations through real world projects that imposed project constraints and perspectives from diverse disciplines and project members, the results generated feedback loops that aided the identification and evaluation of the performance potential of microforests. In addition, the exploratory design case studies investigated the potential interrelationships and combinations of the various identified performance parameters, as well as the performance of the resultant design solutions.

A vegetated courtyard in Accra, Ghana, in collaboration with City Foerster, was the first design case study [5]. This case study investigated the potential of microforests to improve the performance of office buildings (sub research question 1), as illustrated in Figure 1.2. This project was chosen as a design research case study because the project had already been developed to a sufficient level to facilitate the quantification of the building's performance metrics, as well as because the project included a courtyard space that could be designed to integrate vegetation at the scale of a microforest, in a way that could allow for the evaluation of the shading potential of microforests, thereby allowing for the evaluation of sub research question 1.1.1. In addition, the design team had a vested interest in reducing the energy consumption rate of the building, as low energy consumption was an important project goal for the design team, as discussed in Chapter 4. Furthermore, the project was still in the schematic design phase, and therefore the developed design solution could potentially be integrated into the final building design, thereby allowing for post occupancy evaluations of the performance of the design solution in the future.

The second design case study was a typical existing mid-size commercial office building located in Amsterdam, The Netherlands, in collaboration with Deerns Mechanical Engineering [6]. The focus of this case study was on the potential of microforests to improve the ecological performance of office buildings, (sub research question 3). This particular building project was chosen as a design case study because the building owner was interested in investigating different ways of incorporating vegetation into office buildings, at various scales, in ways that would allow him to market the office building as a high performance office environment and successfully lease the workspaces at above average rates. Hence, this design case study allowed for the exploration and evaluation of diverse design solutions that applied diverse previously identified and potential ecological design guidelines, strategies, and metrics. Furthermore, the scale of the office building is representative of the typical scale and scope of mid-size commercial office renovation projects in The Netherlands, thereby providing opportunities for various results of the study to be generalized, when appropriate.

Following these design investigations, several design case studies that were focused on investigating the applicability of the various research findings that were previously developed through the various research processes of the research project, were developed. These design case studies also investigated the potential of microforests to effectively address various building, worker, and ecological performance parameters simultaneously (sub research question 4). To this end, the third design case study was a renovation of an existing 15-story office building in Oslo Norway, called the 'Urban Mountain', in collaboration with a design team that includes Schmidt Hammer Lassen and Transsolar [7]. Due to the developer's interest in integrating vegetation into office buildings in ways that provided economic benefits, including increased worker productivity, this design case study allowed for the evaluation of the application potential of the building and worker performance related research findings that were generated in this research project. Since the design team was also interested in developing a project that was positively performing in terms of ecological performance, and incorporated a biologist into the design team, this case study also provided opportunities to apply some of the ecological performance design strategies, guidelines, and solutions that were developed in this research project. Moreover, the collaborative nature of the multidisciplinary design team allowed for dynamic feedback on potential microforest design solutions.

The fourth and fifth exploratory design case studies were a new construction office building and a mixed use tower in Malaysia, for the architecture office of Ken Yeang [8]. These case studies were primarily focused on addressing worker performance (sub research question 2), while also exploring potential opportunities to integrate building and ecological performance parameters in effective ways (sub research question 4). Similar to the 'Urban Mountain' design case study [7], these design case studies allowed for the evaluation of the application potential of the findings of this research project. In particular, the developers and design teams were interested in increasing worker performance in these projects. It is important to note that these design case studies allowed for the evaluation of the application of the research findings in a different cultural context than the 'Urban Mountain' case study. Moreover, the design teams in these projects were particularly interested in exploring and developing design solutions that generated ecological performance benefits, although with the understanding that design solutions that provide ecological benefits should be developed in a manner that provides economic benefits to the building owner, in order to garner the support of the developer. To this end, the developer was interested in marketing the building as a sustainable project with visible green space, and was thereby open to incorporating microforest design solutions into the project.

In terms of the observation case studies, observations of an existing office building with an integrated spatial vegetation environment, the existing Lumen building in Wageningen [9], provided occupant, design team, and facility manager feedback on the building, worker, and ecological performance of an existing spatial vegetated environment (sub research questions 1-3), as well as potential design strategies and performance parameters to consider in order to improve future design solutions. This case study was chosen because the Lumen building had two vegetated common spaces that were adjacent, and accessible, to the workspaces of the building occupants. These vegetated spaces had been in the building since the construction of the building was completed in 1998. Thus, initial issues with the vegetation spaces, such as ineffective climate systems and external wall assemblies, had been resolved, according to the facility managers. Furthermore, the vegetation in these spaces was denser than when they were originally installed, which generated a more spatial vegetation environment. Furthermore, the potential of the occupants to perceive the vegetated spaces as novel environments, a potential effect that is discussed in more detail in Chapter 6, was also reduced, since the occupants had, at the time of the study, interacted with the vegetation spaces for a number of years. Moreover, the Lumen building included both cellular offices and open floor workspaces, which allowed for the evaluation of the effects of spatial vegetated environments on multiple workspace types. The observation of an existing forest in Delft, The Netherlands [10] provided insight into the potential benefits and constraints of integrating forests into building environments (sub research questions 1-3). This forest was chosen as it represented the typical type of forest that was accessible, and therefore familiar, to residents of Dutch cities on a daily basis at the time of this study.

In order to evaluate the performance potential of microforests, in regards to specific performance parameters, quasi-experiments and surveys were conducted throughout the course of the research project. For instance, the thermal comfort of occupants working within a work space that were filled with dense vegetation, compared to the thermal comfort of occupants within the same building working within a similar work space without vegetation, was evaluated [11]. The thermal comfort of the participants was measured through thermal comfort questionnaires and monitoring of the climate conditions of the test workspaces, throughout the four seasons for one year. In addition, the performance of other performance parameters that were identified in the research questions were evaluated through self-reporting questionnaires. The results of this quasi-experiment were used to determine if the presence of microforests could improve occupant comfort, and potentially, reduce building energy use through the increase of occupant comfort in less actively conditioned work environments (sub research questions 1-2).

Furthermore, the types of spaces knowledge workers prefer to work in for a range of creative and non-creative work tasks, including a number of natural environments, as well as participants' valuation of natural environments, were evaluated through a survey of the knowledge workers within BK City [12]. In addition, the perceived value of various spatial qualities by the same knowledge workers were evaluated for the same range of space types (sub research questions 2-3). BK City was chosen as the context for this study because the building included a diverse range of workspace types. Therefore, the participants of this study had experience working within a range of workspace types, and thereby were appropriate participants to evaluate the relative value of working in diverse workspace types while conducting various work tasks. The appropriateness of BK City for this study is discussed in more detail in Chapter 7.

Descriptive study II phase

The Descriptive Study II (DS-II) phase is the phase in which the results of the research that are developed in the PS phase are evaluated. These evaluations are conducted in order to determine the effectiveness of the various methods and solutions that are tested in the prescriptive phase, in terms of their ability to realize the desired situation. This evaluation process should evaluate both the applicability and effectiveness of the tested methods and solutions.[51] The outcomes of this phase include the identification of necessary improvements that need to be made to the evaluated strategies and solutions to achieve the desired situation, the determination of whether the developed support research sufficiently addresses and contributes to the intended task and research objectives that they were intended for, and whether the developed support has the expected results, among other potential outcomes.

In addition, the results of this phase can be used to develop design support systems, such as methods, guidelines, space types, and tools that improve some of the identified performance parameters, or that evaluate the relative effectiveness of various strategies and solutions to achieve the desired outcomes. Thus, these types of support systems can be used to improve the quality of the identified performance parameters, the problem definition, and the design solutions. Furthermore, this phase can be utilized to identify necessary improvements that may need to be made to the support system to improve its effectiveness.

For this research project, the results of the exploration, observation, and experimentation studies that were conducted in the PS phase were used to evaluate the research hypotheses, and contribute to the development of a range of performance based design strategies and guidelines, high performance case studies and spatial types, as well as performance metrics and evaluations of various types of workspace environments and design strategies.

§ 1.6.3 Results of applied DRM process

Moreover, throughout the DS-I, PS, and DS-II phases, experts from a diverse range of research domains, including environmental and worker psychology, ecology, zoology, and engineering, will provided critical feedback and advice on the development, methodology, and evaluation of the various research processes. This interdisciplinary process will contribute to the development of the holistic, broad scope of the research, and was integral to ensuring the scientific validity of the research.

Similarly, it is important to note that the development and results of the research were communicated to, and received feedback and peer-evaluations from, the broader scientific community via conference papers and presentations, design workshops, collaborative consultations and interviews, as well as peer-reviewed scientific journal publications.

The results of the four DRM phases resulted in the development of research conclusions, design guidelines, high performance spatial types and case studies, as well as performance metrics. In addition, the results of this research project can be applied to current and future building projects in a myriad of ways. For instance, the results of this research project can be used as workspace and microforest space type design guidelines, and can also be used to evaluate the performance of design solutions, in regards to a diverse range of performance parameters. The process and results of this research project, including the scope, methodology, and results of the various studies that were conducted, as well as their application potential, are discussed in the following Chapters.

§ 1.7 Research outline

The discussion of this research project is divided into six sections, as described in this section, and illustrated in Figure 1.3. It is important to note that the development of the contents of these diverse sections allowed for the research questions to be explored and evaluated from diverse performance and design perspectives, thereby increasing the level of validation conducted in this research project. Moreover, this multi-perspective research methodology fostered additional opportunities to identify and evaluate innovative, high performing design solutions and strategies, as well as previously unconsidered performance benefits and interrelationships. Figure 1.4 illustrates the general research questions and potential design applications of the contents of the individual chapters.

The first section of the dissertation provides a review of the background and methodology of the research project in Chapter 1, as well as introduces the concept of microforests, and its general performance potential, in Chapter 2.

In the second section, Chapter 3, the potential of microforests to improve the performance of office buildings and building systems is explored.

The third section presents several case studies that investigated the potential of microforests to improve both worker and building performance. To this end, Chapter 4 presents a design case study that evaluated the potential of vegetation to reduce energy use and improve occupant comfort, through the use of vegetation as a physical shading device, as well as through the provision of semi-outdoor high quality microforest workspaces [5]. This study also examined the relative annual costs of an office building's energy consumption, in comparison to the costs of the occupants of the building. In addition, Chapter 5 presents a quasi-experiment of the potential psychological and physiological impacts of microforests on occupant thermal comfort, which can also potentially impact the energy consumption rate of office buildings [11].

The fourth section explores the potential of microforests to improve worker performance. Chapter 6 draws upon the results of existing literature to explore the potential of the design of work environments to impact worker performance, particularly natural environments such as microforests. Chapter 7 describes a study that evaluated the types of work environments and spatial qualities that promote worker performance, including constructed and natural environments, in terms of a diverse range of work tasks [12].

The fifth section explores the potential of microforests, and buildings in general, to improve the ecological integrity of local ecosystems. The general potential of buildings to improve the ecological integrity of local ecosystems is discussed in Chapter 8. Moreover, three general design strategies to improve the ecological integrity of local ecosystems are identified : design for ecosystem functions, design for ecological behavior, and design for biodiversity. The subsequent three chapters explore the potential of these three strategies individually. Chapter 9 explores the potential of buildings to affect the ecological behavior of building occupants. Chapter 10 explores the potential of buildings to improve the functions of local ecosystems. Chapter 11 explores the potential of buildings to improve the biodiversity of local ecosystems.

The final section reviews the general results of the various research processes of this research project.

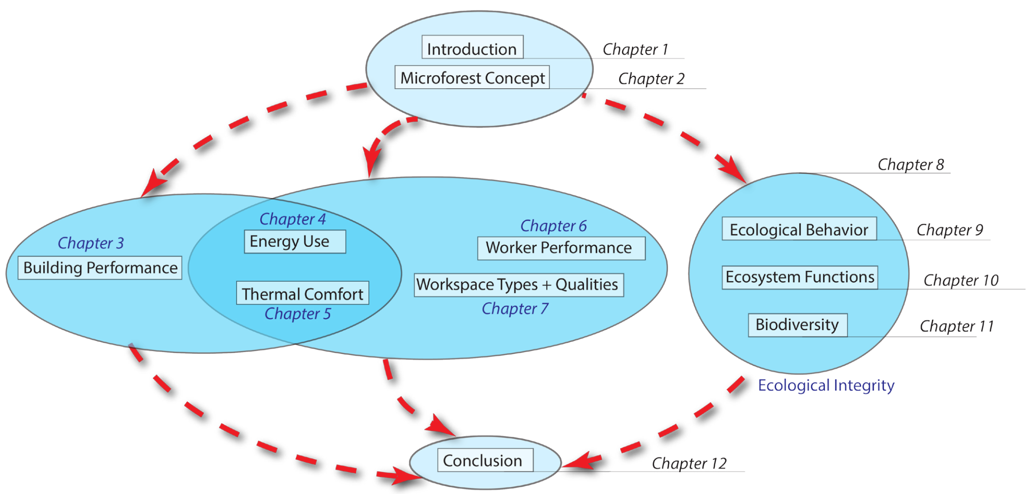

FIGURE 1.3 Overview of book chapters and sections

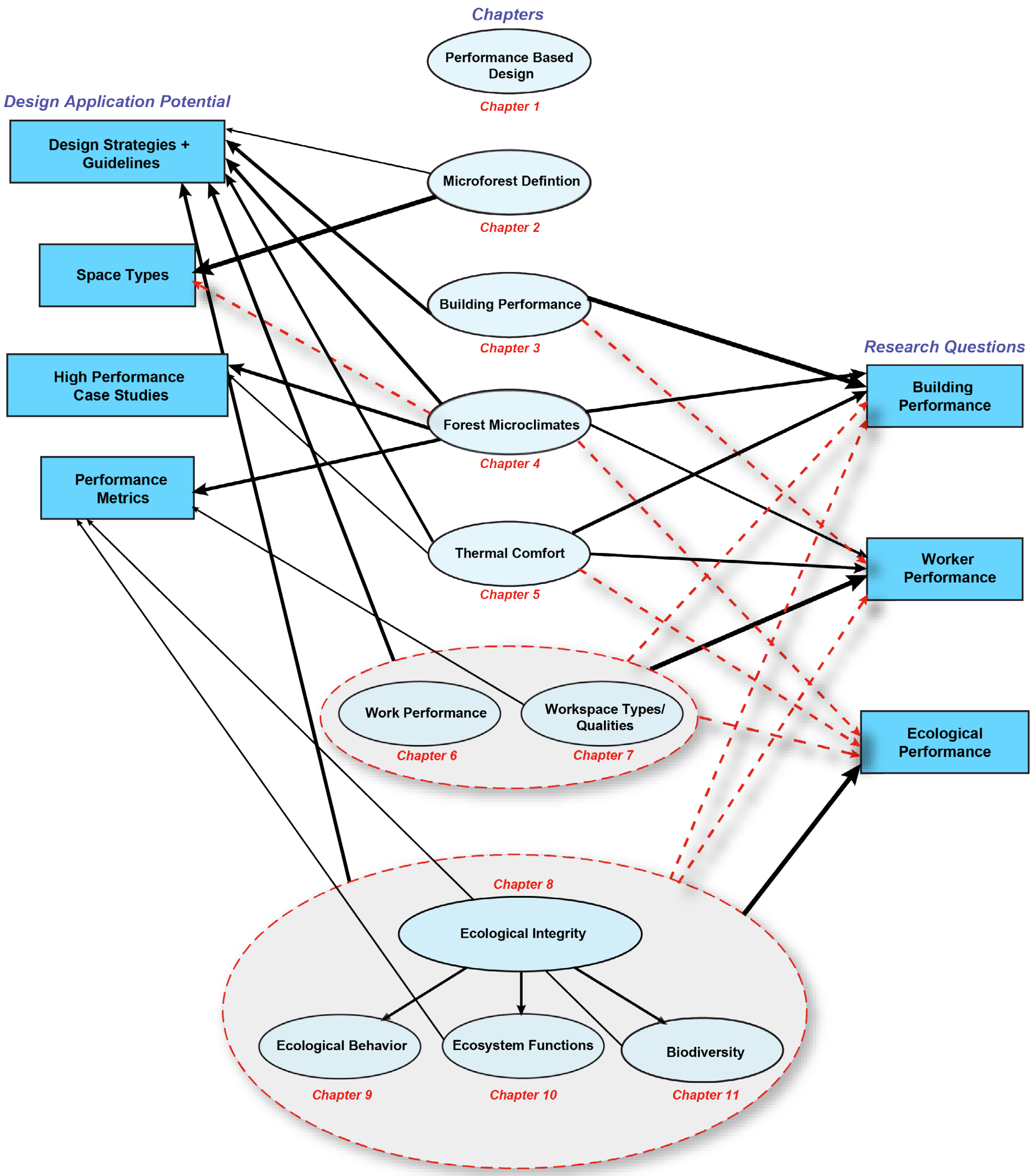

FIGURE 1.4 General research questions addressed within, and potential design applications of, chapter contents

2 Defining Microforests + Exploring Their General Performance Potential

As discussed in Chapter 1, there is substantial evidence that the integration of microforests can improve the building, worker, and ecological performance of building projects. To this end, Chapter 2 defines microforests in greater detail, as well as identifies the general performance potential of integrating microforests into office buildings. In contrast, the subsequent chapters investigate more specific potential performance benefits of integrating microforests into office buildings.

§ 2.1 Defining microforests

§ 2.1.1 Understanding natural forest ecosystems

In order to understand and evaluate the performance potential of microforests, it is important to first develop an understanding of natural forest ecosystems. To this end, the following subsections provide an overview of several design related issues of natural forests that are important to consider when developing microforests.

§ 2.1.1.1 Defining natural forest ecosystems

Natural forests function as ecosystems: they provide the foundation for, and in turn are influenced by, the myriad of interrelationships and processes that are developed between the living organisms and abiotic processes and objects that are present within and around the boundaries of forest ecosystems. Moreover, forests are inherently interrelated to adjacent environments and intersecting ecological processes.

Natural forests provide a diverse array of ecosystem services, including water and nutrient filtration and storage, solar radiation absorption and reflection, food resources, air filtration, and stress reduction, all while supplying healthy air, water, and nutrients.[46, 101, 151, 174, 223, 233] In addition, they provide the habitats and resources necessary for sustaining 80% of the species that are currently present within terrestrial ecosystems, including the largest share of threatened species of any terrestrial ecosystem type.[151]

The physical structure, biological and abiotic organisms and processes, ecological performance, and sensual experience of a particular forest is influenced and developed in part from a number of contextual factors, such as the climate and geographical region it is situated within, as well as the prevalent contextual ecological processes, organisms, and other abiotic factors. These interrelationships influence their performance, in regards to a diverse array of performance parameters, based on the local context. As such, natural forest space types vary throughout the world, from boreal forests in the arctic, to temperate forests in the middle longitudes, to rainforests along the equator.

§ 2.1.1.2 Identifying effective natural forest ecosystem types for integrating into building projects

Since this research project was conducted in The Netherlands, the locally prevalent temperate forest space type was considered as the model natural forest. The temperate forest space type was used in order to determine the potential of Dutch office buildings to contribute to the ecological integrity of local temperate forest ecosystems. Ecological integrity is a normative concept that is used to refer to the state, or health, of an ecosystem. Chapter 8 discusses the definition of ecological integrity in more detail.

Of course, microforests can be developed based on any type of forest. Nevertheless, it is suggested that when considering incorporating a microforest space type into a project, the design team should select an appropriate natural forest ecosystem that is locally prevalent as their model, in order to maximize the ecological, social, and economic performance of the design solution. For example, the incorporation of local vegetation species can reduce the maintenance requirements and costs of interior vegetation, as discussed in Chapter 3, can promote ecological behavior via increasing the rate of the local community's positive interactions with local natural environments, as discussed in Chapter 9, and can provide habitat for local flora and fauna, as discussed in Chapter 11. However, it is important to note that depending on the performance goals of the design solution, local vegetation and forest space types may not always be the most appropriate solution. For example, deciduous trees that shed their leaves in autumn may not be appropriate for interior environments, or appreciated by the building occupants, depending on the design solution. Moreover, the suitability of the climatic conditions of semi-outdoor and interior environments varies by the types of local vegetation species. Thus, it is important for design teams to assess the types of vegetation building environments can support at the beginning of the design process, such as by evaluating the potential of various inherent and designed microclimates within building environments to promote a diverse range of local species.

§ 2.1.1.3 Defining the general structure system of forests

Temperate forests are typically defined as having four to seven structural layers. The seven layers consist of a canopy layer, low tree layer, shrubs, herbaceous plants, soil surface, subsurface root zone or rhizosphere, as well as a vertical vine layer. These seven layers are sometimes compressed into four layers, in order to reduce the complexity of the temperate forest ecosystem into a more manageable organization structure, in terms of problem solving and analysis.[223] Since this project is focused on the design potential of forests, the seven layer, more comprehensive definition is considered to be more appropriate, in order to allow for the consideration of all the layers in the design and performance evaluation processes.

§ 2.1.2 Defining the general potential of microforests

The relatively small scale of interior building environments within mid-size and large scale office buildings makes it difficult to develop an interior forest ecosystem that is resilient, stable, robust, or self-reliant, as discussed in more detail in Section 1.2.3 and Chapter 3. Thus, interior forest environments will typically require active maintenance and oversight.

In terms of ecological performance, existing evidence of the adaptability of a diverse range of species to urban environments indicates that there are a myriad of opportunities for constructed environments to promote the biodiversity of local ecosystems, as discussed in Chapter 11. For instance, although the results of existing literature indicate that the size of habitat patches that can be integrated into mid-size commercial office buildings are too small to foster self-sustaining populations of a range of species, [67, 166, 411] there is substantial evidence that clusters of small habitat patches, such as residential gardens within an urban block, can function collectively as a larger habitat patch in some cases, as discussed in Chapter 11.[125, 172]

Thus, an interior natural environment can function as a micro habitat patch, or microhabitat, and in regards to forest ecosystems, a microforest. For instance, a microforest can provide ecosystem services, such as water storage and filtration, and solar radiation absorption and reflection, albeit at a reduced scale in comparison to a forest ecosystem. When these functions are performed within a building environment, they can be designed to also impact building and occupant performance. For example, a microforest can be designed to filter water and reflect and absorb solar radiation in the summer, while also improving the creativity and comfort of occupants.[46, 254, 293] Therefore, the performance potential of a microforest is also important to consider from the perspective of the building occupants and building infrastructure systems. These potential performance benefits are discussed in greater detail in Chapters 3-7.

Taking these performance perspectives into consideration, a microforest can be defined as: *a dynamic, stimulating, cohesive spatial environment that is composed of vegetation and soil layers that mimic the structural, perceptual, and ecological composition of a forest ecosystem, yet is not large enough to reliably provide the myriad of functions of a robust, mature forest ecosystem.*

The following subsections review a number of general design issues that are important to consider when developing microforests.

§ 2.1.2.1 Microforest vertical layers

From a design perspective, in order to generate a perceptually cohesive spatial environment, microforests should have a high density of vegetation within at least three different vertical levels: floor level (ground cover), seated eye level (understory), and above head height (canopy).[223, 418] In relation to the structural layers of natural forest ecosystems, the floor level includes the herbaceous plants, soil surface, and rhizosphere layers. The seated eye level includes the low tree and shrub layers. The above head height includes the canopy layer. In addition, a vine layer can be present within all three of the different vertical levels. The categorization of the seven structural layers of natural forest ecosystems into three vertical levels is intended to provide design teams a general microforest design strategy, from a perceptual and spatial perspective.

§ 2.1.2.2 Potential microforest program types

Forests, gardens, and parks have been incorporated into a number of existing building projects to provide environments for a variety of tasks and activities, including recreational, horticultural, social, and work activities and tasks. Section 2.3 discusses the performance of specific existing building projects that have integrated vegetation spaces. It is important to note that the optimal activities to consider when designing a specific microforest should be based on the performance goals of the project, including the needs of the building occupants, and the state of the local urban and natural ecosystems.

To this end, the various potential program types of microforests foster different benefits, occupant needs, and limitations. For example, microforests can be designed to provide collaborative and private workspaces within office buildings, as well as lounge space and informal meeting space, among others. To this end, occupant preferences for various microforest environments and typical workspaces, including collaborative and private workspaces, for different tasks are comparatively evaluated and discussed in Chapters 6 and 7. Moreover, Chapter 9 provides a review of a number of activities that have been found to promote ecological behavior when conducted in natural environments.

§ 2.1.2.3 Microforest open/closed systems_Design for maintenance

Microforests can be designed to be either open or closed to the surrounding outdoor environment, or some degree in between. Closed microforest systems are microforests that do not have physical connections with the surrounding outdoor environment. Although some interactions are inevitable, a closed system reduces the amount of unintended interrelationships that influence the development and stability of the microforest. Open microforest systems, which are systems connected with the surrounding outdoor environment, are prone to surrounding flora and fauna visiting, and establishing within, the microforest. The introduction of new species that were not accounted for in the original design can alter the balance of the system. For example, waterbirds can carry embryonic fish, amphibians, and bacteria, thereby adding new species and abiotic factors to the water, such as altering the nutrient concentration of the water body.[433] This would require a change in the water and nutrient filtration system, in order to account for the imbalance. Based on the results of this research project, including interviews with zoo habitat facility managers, ecologists, biologists, and horticulturalists, literature review, and observations of existing spatial vegetated environments, it is clear that the types of plants used, and the type of microforest system that is developed (open/closed) will substantially affect the degree of maintenance and upkeep required to maintain the microforest. For instance, zoo habitats of 1000m^2 and more are developed to mimic ecosystems, but facility managers have found difficulty managing these systems effectively and efficiently, in terms of cost, species presence, and use of biological instead of chemical input materials. These spaces tend to require considerable active maintenance regimes, in order to maintain the stability of the system, such as through pest and invasive species regulation, nutrient regulation, etc. Furthermore, the results of literature review, case studies, and expert interviews indicate that closed systems are much less maintenance intensive than open systems, but still may require considerable maintenance, particularly at the onset of the project.[392, 473, 489] Therefore, microforests should be actively monitored for the first three to five years in order to ensure the stability and resilience of the system.

In addition, the design of the microforest will substantially impact the maintenance requirements of the microforest. As will be discussed more in detail in Chapters 8,10, and 11, diversity is one of the most important guidelines for developing a healthy, stable microforest. In particular, the diversity of structure, vegetation species, climate, and soil types are important design factors. Although a more detailed overview of maintenance is necessary, it is outside the scope of this book. Jacke (2005) provides a more detailed review of effective forest maintenance regimes.[223]

§ 2.1.2.4 Differentiating microforests from other vegetation design space types

FIGURE 2.1 Planter in Prague Congress Center, Prague, Czech Republic

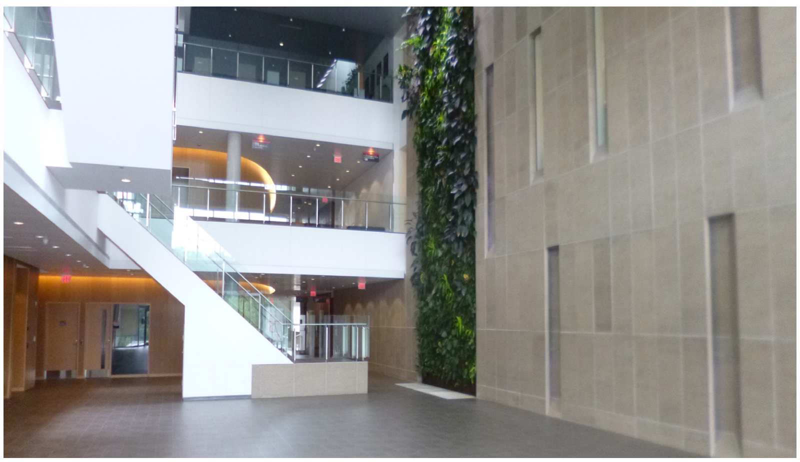

FIGURE 2.2 Green wall in Canal Research Building in Carleton University, Ottawa, Canada

FIGURE 2.3 Garden in Lumen Building, Wageningen, The Netherlands

Living Surfaces *(non spatial)*

Living surfaces, the most common of which being green roofs and green walls, such as in Figure 2.1, are becoming increasingly prevalent within and around building environments. These systems involve planting vegetation within a growing medium as part of a traditional building surface: a roof or wall of a building. *Living surfaces* have less potential to interact with building occupants than microforests or gardens. This is because they are inherently more static, non-interactive, and non-stimulating two dimensional surface applications, rather than dynamic, interactive spatial environments. For example, green walls are typically located in circulation spaces in order to maximize exposure to building occupants and visitors. However, this design strategy minimizes their effect on, and interaction with, people. This is because their interaction with the vegetation is momentary and indirect, such as passing by a green wall on the way to a meeting. Moreover, green walls and roofs tend to have considerably greater construction costs, due to the required extra structural support, than other vegetation systems, such as planters and gardens,[489] as will be discussed in more detail in Chapter 3. Green roofs are sometimes developed into more three-dimensional vegetation environments, such as gardens, which in turn makes them more effective, as they are more interactive. However, intensive green roof strategies also require greater construction and maintenance costs. These initial costs can be offset by long term gains in occupant well-being and performance, if the vegetated space is designed to interact with building occupants in effective ways. For example, extant research, and the results of this research project, indicate that direct interactions between building occupants and natural environments result in a greater diversity and scale of benefits to the performance of the building, building occupants, and local ecosystem.[233] These issues will be discussed in greater detail in Chapters 6 and 9.

Planters

Planters, such as those shown in Figure 2.2, offer a lower cost interior vegetation solution than living surfaces, and can be distributed throughout a building. Planters have the additional advantage of being able to be mobile. However, it is important to note that planters, in regards to a per plant comparison, can cost 30% or more than plants within a living environment.[489] Moreover, in terms of maintenance, planters tend to require substantially more maintenance than living environments. These issues are discussed in greater detail in Chapter 3. Furthermore, although planters may provide opportunities for direct interaction, living environments are more effective in terms of providing opportunities for beneficial interactions between people and natural environments, as discussed in Chapters 6 and 9.

Living Environments *(spatial)*

Spatial environments provide more opportunities for direct interaction between occupants and nature, because they are inherently more interactive, dynamic, and stimulating.[199, 360, 417] People can walk by a garden indirectly, sit within a microforest to have a conversation or pause from work for a moment, or even tend to the maintenance of a specific plant they have become fascinated with.

Gardens

The term *garden* in this thesis will refer to the common western garden styles, such as the modern interior garden illustrated in Figure 2.3. Forest gardens, permaculture gardens, and other more three-dimensional, polyculture garden design strategies can be more closely related to microforests, depending on their design. Thus, they may be classified as either a garden or microforest within this definition structure, depending on the design solution. Gardens are typically constructed on a ground surface. Within the context of a building, gardens can be grown on wall, floor, or roof surfaces. They are composed of ground level vegetation layers, including shrub and herb layers. A key difference between gardens and microforests are that gardens generally do not include canopy layers. For example, agricultural gardens typically avoid canopies in order to maximize their crop yields. However, gardens do sometimes incorporate vertical layers, such as vine layers of tomatoes, grapes, and hedera helix.

§ 2.2 Microforest performance potential

As previously stated in Chapter 1, this research project is focused on the potential of microforests to improve the performance of building projects in regards to three general performance categories: the building, worker, and ecological performance of a given building project. There is a considerably vast breadth and depth of possibilities within these three general performance categories. For instance, natural forests provide a variety of ecosystem services, which are enumerated in more detail in Chapter 10. These services can be developed at the microforest scale as well. For example, microforests can produce agriculture with minimal maintenance inputs (i.e. forest gardens), filter the interior air supply, shade the interior building environment in the summer, and increase the local soil fertility (revive destroyed local soil communities), among other services.

An extensive investigation of all the possible performance benefits of microforests within these three general performance categories is outside the scope of this research project. A more detailed overview of this issue and its resolution within the framework of this research project is provided in Section 4, the Research Limitations section of this chapter. Generally, the performance potential of specific high value performance parameters within these three general performance categories, such as worker creativity, thermal comfort, and the ecological integrity of the local ecosystem, and their potential interrelationships, are investigated and developed in this research project. Furthermore, it is important to note that existing research, as well as the results of this research project, indicate that design solutions that engage multiple performance parameters simultaneously can result in greater performance benefits and higher quality design solutions.[296]

Therefore, the potential of microforests to be integrated into the building infrastructure of building projects, private and public work environments, as well as local natural ecosystems, constitutes an integral part of this research. For example, the integration of the design of workspaces, including microforests, into the design of climate systems was found to be able to reduce building energy use, while simultaneously improving worker performance, as discussed in Chapters 4,5, and 7. Moreover, the various potential interrelationships and benefits between various performance parameters are discussed throughout the dissertation in greater detail, from a diverse range of performance and design perspectives. It is important to note that through the course of this research project, microforests were determined to be able to provide integrated design solutions that were able to improve the performance of individual performance parameters, as well as the holistic performance of the project simultaneously. This was only able to be achieved by investigating the potential benefits of integrating the design of building spaces into the design and performance of the building infrastructure systems, as well as the potential of the design of building spaces to improve worker performance and comfort, as well as the local ecosystem.

Thus, microforests can be developed in a manner that results in symbiotic interrelationships between people and natural environments. In fact, there is a growing body of evidence that indicates that these interrelationships used to exist between Native Americans and the North American forest ecosystems, as well as currently among indigenous cultures throughout the world. For instance, the pre-colonial agroforestry techniques of Native Americans in the Mid-Atlantic region resulted in marked increases in the biodiversity of the local temperate forest ecosystems, which benefitted the local wildlife while increasing the food sources, medicines, fibers, and fuels for the local Native American communities.[223, 370] Thus, forest ecosystems have already been developed to symbiotically benefit natural ecosystems and human communities. Microforests are a means to rediscover and further explore these benefits at the building scale.

§ 2.3 Microforest application potential

In discussions with horticulturalists, developers, architects, engineers, and building owners, one of the most frequently cited issues they have with integrating plants into building environments is that this 'unproven' technology is unreliable. This is a bit ironic, since vegetation has been integrated into the built environment for centuries, if not millenia. It is only recently that the distinct perceptual and physical divide between natural environments and human environments has existed.[296] Historically, vegetation has been utilized to moderate the microclimate of buildings, from channeling wind through Roman Villas for natural ventilation to utilizing climber plants and deciduous trees to shade exterior facades and cool courtyards in various cultures and contexts throughout the world. Diverse vegetated environments have been integrated into buildings to improve occupant performance and well-being. They have functioned as restorative environments in the arcades and courtyards of villas, palaces, and public and commercial buildings, from the ancient Chinese and Japanese gardens, to medicinal and agricultural gardens in European monasteries, to Victorian greenhouses throughout Europe, to healing gardens in modern hospitals and lounge space in contemporary office buildings throughout the world.

As discussed in Section 1.2.4, in modern building environments, vegetation is integrated into projects as planters, living surfaces, gardens, and also microforests. In terms of vegetated spatial environments, gardens and microforests have been incorporated into a diverse range of interior spaces, such as the semi-outdoor courtyards of the Lumen research building in Wageningen, The Netherlands, as shown in Figure 2.3, the atrium of the Ford Foundation building in New York City, the atrium of the Ministry of Finance in Den Haag, and the interior social space of the Brookdale Vernon Hills assisted living building in Illinois. However, these vegetation design solutions are typically not designed from a performance perspective. They are largely incorporated from an aesthetic perspective, or from a general understanding that plants improve worker and building performance. This is partly because the potential performance benefits of effectively integrating plants into building environments have not yet been rigorously quantified and qualified, and are currently relegated to generalizations and assumptions. In general, the reliability and general applicability of the results of existing research varies, and variant design solutions utilizing vegetation have not been compared and evaluated. For example, the effect of having a view of one plant, compared to the effect of directly interacting with a plant, compared to directly interacting with a natural environment, such as a garden or forest, are not well understood. This lack of clarity makes it difficult to effectively apply extant research results into the design of work environments, and to evaluate the effects of design solutions on worker performance. These design issues have led to generalized, ineffective work environment solutions.

Moreover, facility managers and mechanical engineers tend to have a number of concerns, in regards to the installation of abundant vegetation in built environments. These concerns are frequently due to issues such as moisture levels, mold growth, and the lack of reliability of the physical properties of vegetation for engineering calculations, among other issues.[25, 40, 489] However, the results of existing research indicate that a number of these concerns may, in part, be due to a lack of information. To this end, this research project evaluates the validity of several existing concerns. For example, the lack of reliability of plant growth rates and leaf density is sometimes cited by mechanical engineers as a limiting factor for integrating vegetation into mechanical systems.[25, 40] To this end, the physical shading effect of plants has been documented for a number of species, and an average shading value can be established from the results of existing research, as discussed in more detail in Chapter 4. Nevertheless, further research is needed to determine reliable growth rates of various plant species in a variety of indoor environments. Moreover, the ability of various species to maintain a consistent leaf density throughout the lifespan of the building, and the maintenance regimes required to sustain these densities, are other issues that have been mentioned. Another common issue raised is moisture content. To this end, the results of the thermal comfort quasi-experiment detailed in Chapter 5 indicate that interior plants do not significantly affect the moisture content of the indoor environment. However, it is important to consider that water is a larger determinant of plant evapotranspiration rates than solar radiation levels, and the vegetation in the quasi-experiment were only watered once a month, and frequently did not have abundant water in the planters.[345] These issues could have been contributing factors to the relatively similar moisture content levels that were measured in the experiment rooms throughout the test year, regardless of the presence of the plants in the rooms. Nevertheless, these results are in agreement with existing research findings. For instance, Costa (1999) found that plant transpiration levels in office environments did not exceed building code standards for interior moisture content levels.[101] Further rigorous research into these issues may provide additional insight into the performance potential and limitations of interior vegetation.

Thus, the results of existing research and this research project indicate that the integration of vegetation into building environments has substantial precedence, and can provide a diverse array of performance benefits, although a number of these potential benefits have yet to be rigorously identified, explored, and evaluated.

§ 2.4 Research limitations

An arguably common problem that pervades PhD research projects is that the researcher's initial ambitions for the scope of their research project becomes tempered by the reality that the PhD is not a lifelong project, and that it unfortunately cannot solve all of the world's problems. Thus, the researcher is forced to impose limitations on the scope of their research project, either by themselves, their supervisors, or some combination in between, depending on their level of enthusiasm and level of connection with the *real world* (which includes time limits, budgets, sanity, etc).

Therefore, although microforests can improve the performance of a broad range of performance parameters, as partially illustrated in Figure 2.4, this research project was focused on a narrow range of performance parameters. The performance parameters that were investigated were the parameters that the results of the Research Clarification phase of the project indicated had a high performance potential, as outlined in Chapter 1, and discussed in detail throughout the subsequent chapters of this book.

For instance, water filtration and storage is an important potential microforest performance parameter. However, industrialized economies and societies have currently artificially devalued the monetary as well as societal value of water, which in turn makes design for water performance less feasible at the building scale. Microforests can also provide agriculture, and in doing so, can use the interior CO_2 as a resource. However, it is important to note that plants grown through greenhouse methods are typically grown at stressed levels. Therefore, views of these stressed plants may not be visually appealing, and may have a negative effect on occupant well-being, since viewing stressed plants may induce stress in the observers. Further research into the relationship of the health of plants and their effects on people is suggested. Fortunately, alternative, sustainable food growing techniques are available, such as forest gardening and permaculture strategies, which can alleviate these adverse effects, and may possibly be more efficient and effective than typical modern growing techniques.[223] In addition, food production at the building scale can be limited by a number of factors, such as ease and cost of maintenance and harvesting within a given building environment, the ease and cost of transportation of growing materials, etc. However, microforests offer a unique opportunity: a year-round conditioned environment. Therefore, microforests could provide rare fruit that are difficult to grow and require substantial maintenance, such as more flavorful species of apples that are not grown by the agricultural industry because they are not as hardy or productive as the less flavorful yet more durable species that the agricultural industry currently produces. In this fashion, buildings can become a rare food resource that inherently connects people with their local environment.

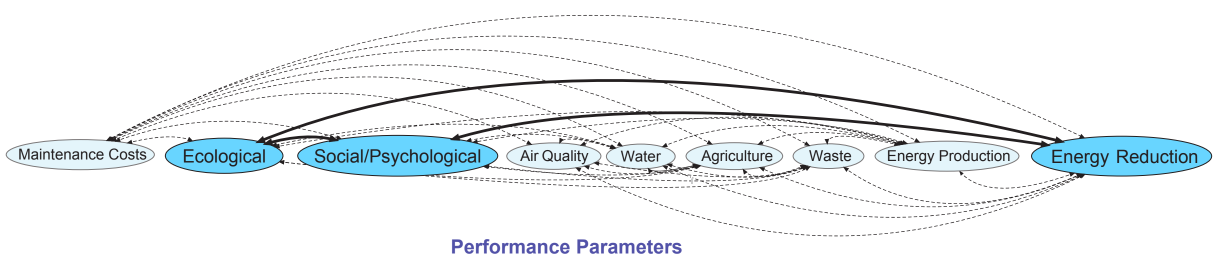

FIGURE 2.4 Potential microforest performance parameters

Although the performance potential of multiple natural inputs, such as water, earth, sun, and plants, is important and significant, this research project is focused on the performance potential of vegetation due to time constraints and the desired level of research depth. This research project is focused on the scale of individual office spaces within mid-size office buildings, in order to rigorously identify, develop, and evaluate potential beneficial physiological and psychological performance parameters of microforests. In addition, workers within office environments have the freedom to relocate their location at an hourly, daily, and seasonal scale, as opposed to school environments, hospital rooms, assembly spaces, etc. These conditions allow for analysis of the potential of a range of spaces, as opposed to singular or concentrated spaces, such as a classroom. The results, however, can be applied to other building space types. Nevertheless, it is important to note that specific performance parameters, such as worker productivity, creativity, and space use rates, may not be directly applicable in some cases.

§ 2.5 Chapter Conclusion

Thus, the integration of natural environments into constructed environments, such as microforests, is currently relatively unexplored, yet can generate a diverse range of performance benefits. To this end, the following chapters identify and explore a number of diverse opportunities for microforests to improve the building, occupant, and ecological performance of building projects. For instance, Chapter 3 explores potential ways in which microforests can improve building performance.

3 Building Performance

As discussed in Chapter 2, the focus of this research project is on the potential of the design of building environments, and microforests in particular, to improve the performance of building projects. From this perspective, the performance of a building, its infrastructure, and its occupants can be organized into three general performance categories: building performance, worker performance, and ecological performance. This chapter is focused on exploring the potential of microforests to improve the performance of buildings and building systems.

§ 3.1 Defining building performance

Building performance can be defined as the overall performance of the parameters of a building project that are related to the construction and maintenance of a building and its infrastructure, including the quantity and costs of building construction, maintenance, furniture, and resource consumption. Therefore, this definition includes the performance of a building's consumption of resources, such as energy, water, and building materials, as well as the space use rates and efficiency of the building spaces and programs. In contrast, the costs of the occupants, including occupant comfort, well-being, and productivity, are considered part of worker performance, and will be discussed in more detail in Chapters 4 and 6.

In regards to developing projects for optimizing building performance, building owners and developers typically focus on optimizing construction costs. However, as much as 75% of the total building costs over the lifetime of a building are operating costs.[72] Therefore, a building project that has good building performance has low operating costs, such as when it is designed to minimize maintenance and resource consumption, as well as provides efficient and effective program space.

Microforests can significantly improve the building performance of a building project in a myriad of ways. As previously discussed in Chapter 2, a comprehensive review of the diverse range of potential benefits that microforests can provide is outside the scope of this research project. Thus, this research project was focused on a number of building related performance benefits that a review of existing research identified as being relatively high value and beneficial, in comparison to other reviewed benefits. These potential high value benefits are outlined in this chapter, and are summarized below:

High Potential Building Performance Benefits of Microforests

- Construction Costs
- Maintenance Costs
- Space Use Rates + Space Efficiency/Effectiveness
- Building Resource Consumption Rates *(Microforest as building infrastructure)*

TOC

§ 3.2 Construction costs

§ 3.2.1 Current level and type of integration of vegetation into office building environments

Plants are commonly found in many office environments throughout the world, from the provision of individual houseplants to more extensive installations, such as green walls, roofs, and gardens. For example, the Ford Foundation Building in New York and the Lumen Building in Wageningen, The Netherlands, incorporated accessible interior garden atrium spaces as key social spaces. In addition, there are several examples of interior vegetation providing building system services, such as the Covent Garden within the European Commission's headquarters building in Brussels,Belgium filtering a majority of the building's wastewater, and the Northeast Mississippi Community College science building's plant filled atrium that filters the building's air and restroom wastewater.[480]

Furthermore, plants are commonly incorporated into office environments by office managers due to a belief that plants improve worker performance. Moreover, plants are also installed simply because office workers prefer the presence of plants in their work environment.[199, 278, 418, 423] Indeed, as discussed in more detail in Chapter 5, the participants of the thermal comfort quasi-experiment conducted during this research project consistently remarked that the presence of plants improved the quality of their work environment, their sense of personalization of the space, and their overall comfort.[293] Furthermore, building owners and developers that wish to market their buildings as 'sustainable', are increasingly asking architects to incorporate vegetation into their designs, and architects are increasingly incorporating vegetation into their design solutions to win sustainable design competitions, as well as in an effort to improve the sustainability of their projects.[489] To this end, the author was invited to take part in several design competitions and professional building projects throughout the course of this research project, with the goal of developing design solutions that maximized the potential performance benefits of integrating vegetation into building projects. For instance, the 2013 Nordic Built Challenge in Oslo, Norway was won, in collaboration with Schmidt Hammer Lassen Architects and Transsolar, by developing a building that integrated spatial vegetation into the design, wherein the performance goals were to filter the internal air and improve worker creativity and productivity. It is important to note that the jury and developer expressed direct interest in integrating interior vegetation spaces into the project, with the condition that the vegetation provided benefits in an effective and rigorous manner that would justify their additional initial expense.

Although vegetation is already prevalent in existing workspaces, the integration of vegetation into building environments in ways that maximize their potential performance benefits is still in its adolescence.[457, 473, 489] In fact, the lack of integrating vegetation in ways that maximize their performance has led to the removal of vegetation in a number of building environments. For instance, a twenty year old garden in the atrium of the downtown office tower, Sun Life Financial Center, in Ottawa, Canada, is in the process of being removed because the building owner does not perceive the vegetation to be adding value to the project. In this case, the developer perceives the vegetation solely as an increased maintenance costs.[217]

The design and development of performance based microforests can offer an economical and high performance design solution that provides diverse, direct benefits and value to the building occupants and owner. For instance, although it may seem counterintuitive, microforests can reduce the construction costs of a building project, as described in the following subsections.

§ 3.2.2 Initial cost of plant type and growing medium (soil vs. hydro)

The initial cost of plants depends on the plant type, as well as the container and growth methods, as illustrated in Table 3.1. In terms of container based plants, hydroponic plants are easier to maintain than soil based plants, as well as tend to have a longer lifespan.[29] In addition, there is existing research that indicates that hydroponic plants are more effective at filtering air, since the more open substrate allows oxygen and other atmospheric gases to be drawn into the root area more easily.[480] Hydroponic plants are now the office plant of choice in Europe.[38, 489]

PLANT GROWTH METHOD	180MM *(HEIGHT)*	30MM *(HEIGHT)*
Hydroponic plant	100-150 €	20-25 €
Soil based plant	50-100 €	10-15 €
Container	80-100 €	20-25 €

TABLE 3.1 Plant costs based on growth method and size

Note: Values are based on cost estimates from local horticularalist[489]

However, as shown in Table 3.1, hydroponic plants have a substantially higher initial cost, approximately 30-50% more than soil based plants. Moreover, hydroponic plants must be grown using special growth strategies so that they can survive without soil. This process makes the selection of hydroponic plant species quite limited.[489] These limitations have negative consequences on building occupants. For example, the use of a limited selection of hydroponic plants in office spaces throughout the world is contributing to the generation of homogenous, placeless office environments that disconnect occupants from their local ecosystems and communities, and adversely affect their work performance. Moreover, the use of hydroponic plants reduces the potential of growing locally prevalent vegetation in the office environment, thereby further reducing the potential of office buildings to positively impact the ecological integrity of the local ecosystem. These design issues are discussed in more detail in Chapters 6, 10, and 11. Furthermore, different hydroponic plants require different fertilizers and containment systems, which can make it difficult to use these types of systems for microforests.[478] In contrast, soil based plants that are housed in containers typically require greater maintenance and have shorter lifespans, with an approximate maximum lifespan of 10 years with maintenance. According to horticulturalists, longer lifespans can be achieved with more intense and expensive maintenance.[489]

Furthermore, typical office plants are housed in containers, regardless of the plant growing medium. As illustrated in Table 3.1, these containers can be as much or more than the cost of the plant, depending on their size, quality, style, and plant growth method. However, it is important to note that building owners and managers can receive a discount when buying containers in bulk. For example, Zuidkoop, a horticulture company in The Netherlands, offers a 30% discount on containers if approximately 200-300 plants are purchased.[489]

Thus, the initial cost of microforests can be more cost effective than more common planting strategies. For instance, since the plants are established within a common soil base, the initial costs of the plants are lower. Furthermore, in comparison to typical container based office plants, microforests reduce the need for containers, by growing the plants in a common container of plants. In addition, by purchasing the plants in bulk, significant cost savings can be achieved. For example, Zuidkoop offers a 15% discount on purchases of 100 plants or more.[489] Moreover, the initial costs of plants can be significantly reduced if the plants are harvested from the local natural ecosystem. This strategy has been conducted successfully in modern green roof projects in Switzerland, as well as in traditional green roofs and gardens developed in various cultures and countries throughout the world.[62] Furthermore, if a microforest is located on interior floor levels, the structural requirements will be less in comparison to a green roof. This is because the structure of typical roofs is considerably less than interior floor plates, because they do not need to support as much loads. Due to the need for increased structural support, among other factors, green roofs tend to cost at least three times more than typical roofs. For additional reference, green walls tend to be on average ten times more expensive than green roof systems.[489]

However, it is also important to note that the structural types of vegetation incorporated into a microforest will influence the construction costs. For instance, although both trees and vines can contribute to the generation of a canopy layer, trees tend to have more weight, and can have more expansive root systems. This additional weight and possible soil requirements, will, in turn, increase the structural costs of the floor plate. Moreover, vegetation in adolescent stages have different nutrient, soil, and water requirements, as well as evapotranspiration and growth rates, among other performance parameters, than mature vegetation. The same is true for different types of vegetation, such as coniferous and deciduous trees.[223, 345, 428] Thus, the types of vegetation, and density of various types of vegetation within a microforest, are important design factors to consider, in terms of construction cost performance. Similarly, the relative accessibility of the various layers impacts the cost of their maintenance, and should be taken into consideration during the design process. For instance, depending on the design solution, the canopy layer can be more time intensive to trim than shrubs, due to the relative height of the leaves and branches. Maintenance cost issues are discussed in more detail in the next section.

§ 3.3 Maintenance costs

Typical vegetation maintenance costs include nutrients, pest control, regular labor such as pruning and observation, transport, and replacement costs and fees (replacement fees are commonly included in maintenance costs when the plants are leased from a company). The maintenance costs of plants depends on a variety of factors, including the quantity of plants, their relative location and arrangement within the building, as well as if the plants are leased or owned, and if they are maintained by the company occupying the building or a horticultural company. For reference, a Dutch horticultural company, Zuidkoop, charges 35 € per plant per year for 50-100 hydroponic, container based plants. This cost can be reduced to 23-25 € per plant per year if the building houses over 300 plants. In contrast, a small quantity of plants have greater maintenance costs per plant. For example, 10 container based hydroponic plants cost 60-80 € per plant per year.[489] Maintenance is required approximately once a month for hydroponic based plants. However, there are exceptions: large plants which are over 3m in height, or plants with high evaporation rates, such as bamboo, require maintenance approximately every two weeks. Soil based plants have higher maintenance costs, as they require water once a week in the summer, and approximately once every two weeks in the winter.

In contrast, the construction and maintenance costs of a bed of plants is significantly less. It is also important to note that since a large portion of maintenance costs involve labor costs, the maintenance costs of plants will significantly vary by country, as well as the company's decision on whether to maintain the plants 'in-house'. According to Zuidkoop, the annual maintenance costs for a small bed of 20 soil based plants of 1-2 m height are 35 € per plant, including a replacement fee.

The same quantity of soil based plants in containers would cost 42 € per plant per year. Thus, a small bed of plants results in approximately 16.6% annual savings in maintenance costs. The savings are considerably more for a larger bed of plants, such as a microforest. The annual maintenance costs for a 20m^2 bed of soil based plants were quoted to be approximately 27 € per m^2, or approximately 18.5 € per plant, including a replacement fee. Thus, the maintenance costs for a microforest are approximately 47.1% less per plant than typical office plants. These savings account for the reduction in maintenance time achieved by centralizing the location of plants, instead of distributing them throughout the building. These estimates do not include the reduced maintenance fees that can be achieved through automated irrigation strategies, reduced weeding, and other maintenance benefits that the centralization of plants provides. In other words, a distributed planter vegetation strategy is substantially more cost intensive than a centralized microforest, in terms of maintenance costs.

These maintenance costs can be lowered even more, depending on the microforest design and planting strategies. For example, some of the perceived 'negative' aspects of plants in the work environment, such as leaf litter on the office floor, are reduced, or even eliminated, in a microforest planting strategy. In the case of leaf litter, this 'waste' material can become a nutrient resource for the soil and sub–surface soil community, and helps minimize irrigation demand by reducing soil evaporation losses. Moreover, labor intensive maintenance, such as pruning and trimming plants for aesthetic purposes, is one of the typical plant maintenance services within office environments, and is most frequent when vegetation is grown in planters. This is because vegetation in planters are perceived by occupants in a similar way as sculptural objects, since they are perceived as isolated instances of nature within a contrasting constructed environment. By planting the vegetation in groups, and developing a microforest design aesthetic for the vegetation, the individual elements of individual plants are less noticeable, and the growth of the plants may be perceived positively. Indeed, the resulting 'unkempt' or 'wild' appearance of the microforest can at best be perceived as aesthetically pleasant, thereby obviating the need for trimming, and at worst, the growth of the plants are less noticeable, thereby reducing the amount of trimming required. The types and combinations of plant species also impacts the maintenance requirements of the microforest. When microforests support a diverse range of species, they tend to require less resources and maintenance.[489] Moreover, plants with mutualistic relationships should be selected, in order to reduce the negative effects of competition between certain plants, which can increase the relative maintenance requirements of the vegetation.[223]

Furthermore, the irrigation and supplemental nutrient demand of vegetation can be reduced when they are grown in groups. Automatic irrigation systems are not cost effective for individual planters. However, by grouping the vegetation, low cost automated irrigation systems, such as drip irrigation systems, can be cost effective solutions. [489] In addition, plants grown in groups tend to use less water, and soil based group planting strategies can minimize supplemental nutrient demand through the development of a healthy soil and sub-surface soil community. It is important to note that typical artificial fertilizers tend to eradicate the beneficial soil community.[223] In addition, the use of virgin top soil should be avoided, as there is a global deficiency in this resource, and the harvesting of virgin top soil typically destroys valuable peat bog ecosystems.[223, 489] When allowed to thrive, this healthy soil community can provide much of the nutrients plants require, which in turn reduces the nutrient maintenance requirements of the microforest. In addition, understory plants are essential for providing nutrients in the soil. They provide a much greater quantity of nutrients than overstory plants.[223] Although microforests can provide additional benefits to the maintenance costs of office buildings, a more extensive discussion on this topic is outside the scope of this research project. Jacke (2005) provides a more detailed overview. Nevertheless, it is apparent that the development of microforests inherently reduces the maintenance costs of large scale and small scale vegetation interior environments.

§ 3.4 Space use rates + space efficiency/effectiveness

Microforests can be designed in ways that provide additional high performance workspaces, increase workspace use rates, and improve occupant comfort and performance. Specific effective workspace and microforest design strategies, in terms of improving worker performance, are discussed in Chapters 6 and 7. Furthermore, the provision of high quality workspaces can directly improve building performance, in terms of resource consumption rates, space use rates, and the efficiency and effectiveness of space. For instance, Chapter 4 reviews an explorative case study that found that the provision of a microforest can provide additional work spaces that promote improved work performance and comfort, while also reducing the energy consumption of the building, both via psychological and physiological means. Thus, the design of space, particularly in consideration of potential integration opportunities of building spaces with building systems, can improve the effectiveness of the space, in terms of a broad range of performance parameters.

§ 3.4.1 Existing need to make more effective workspaces

In order to design spatially effective microforests, the operation and use of typical office environments must first be understood by the design team. Employees tend to use different workspaces depending on the work task they are currently engaged in, and tend to work on different worktasks throughout the course of a given day. In fact, workspaces used by individuals can vary hourly, daily, weekly, and monthly.[114] For instance, individual workspaces within office buildings are not continuously occupied throughout the workday. Indeed, as much as 60% of assigned workspaces in typical office buildings have been found to be vacant at any given time because people are in meetings, site visits, vacations, sick leave, etc.[100] Furthermore, office workspace utilization rates have been found to be as low as 14%.[334]

These underutilized workspaces represent significant operating costs and sources of resource consumption, as these spaces tend to be climatically conditioned, contribute to the quality of the indoor air, contribute plug loads, and receive lighting from the overall lighting scheme, among other influential factors.[468] Furthermore, perpetually empty workspaces are unnecessarily cleaned, require furnishing and technology resources, and could alternatively be used for providing a building program that is useful to the occupants. In some cases, underutilized workspaces can be eliminated from the building footprint altogether. Thus, there is currently a need, and thereby opportunity, to make the design and use of workspaces more effective.

§ 3.4.2 Identifying types of effective workspaces

In addition, existing research indicates that knowledge workers conduct a range of tasks in a variety of workspaces, and the types of spaces used to perform different tasks, as well as the amount of time devoted to different tasks, varies by individual, due to a number of influential factors.[114, 127, 382] Therefore, the development of diverse, high quality formal and informal meeting spaces, as well as individual work spaces, that are conducive to a range of tasks, are essential for developing a high performance work environment. To this end, Chapters 6 and 7 discuss in detail the spatial qualities and types of workspaces that have been found to be perceived as high quality and high performing in existing research, as well as in studies conducted as part of this research project.

The integration of occupiable spaces into microforests provides opportunities for these spaces to provide performance benefits, even when these spaces are not occupied. These types of integration strategies can also reduce the costs and resource consumption of the workspaces of a building. For example, a standard 8 person, 20 m^2, 3.6 m floor to ceiling height conference room cost approximately 39,000 euro to build in 2013, according to Royal Haskoning DHV. Moreover, the air ventilation, heating, and cooling systems are generally oversized for these rooms, in order to accommodate the inherent rapid shifts in the occupancy rate of these types of spaces. However, even with the provision of oversized climate systems, conference rooms are typically a source of poor air quality and poor thermal comfort.[25, 40, 473]

In contrast, if a conference room were adjacent to an atrium, and was ventilated by directly opening the conference room wall assembly to the larger atrium space, then the conference room could passively accommodate sudden shifts in occupation rates while maintaining indoor air quality. This would make the need for investing in a dedicated ventilation system for the conference room unnecessary. To this end, the removal of the ventilation system in one conference room would reduce the cost of the conference room by 10,000 euro, according to Royal Haskoning DHV. Although this design solution would shift the ventilation load to the atrium, the presence of a microforest within the atrium would reduce the ventilation load of the atrium. Furthermore, the larger atrium space would have a lower ventilation rate, due to the larger air volume the atrium supports, In addition, if a number of atrium adjacent interior spaces are passively ventilated to the atrium, considerable cost savings can be made to the building's ventilation system, by centralizing the active ventilation system within the atrium, rather than within the individual rooms.

In addition, if the conference room were located within a microforest, significantly greater construction savings could be made by reducing material and climate system costs, and potentially designing the space to be multifunctional. However, the design team should first determine which program spaces can benefit from being multi-functional. Furthermore, in order to incorporate building program spaces successfully into microforests, the design team must understand what types of building spaces and worktasks will benefit the most from being integrated into microforests.

To this end, an investigation of the types of workspaces and worktasks that benefit from being performed in a microforest was conducted as part of this research project, and is discussed in detail in Chapter 7. In general, the results of this survey indicated that microforests are preferred for a range of worktasks, and are perceived as suitable for every evaluated work task. Therefore, spaces within microforests can be designed to be multifunctional, thereby providing space for multiple required program spaces simultaneously, which in turn further reduces construction costs.

From a worker performance perspective, the provision of adaptable workspaces that provide the resources necessary for multiple work tasks can improve worker performance, by reducing the need to switch spaces for conducting various work tasks. However, it is important to note that existing research indicates that informal meetings and chance conversations with co-workers, such as those that occur when switching workspaces, can also positively impact work performance and lead to new collaborations and ideas.[115, 462] Nevertheless, existing research indicates vegetation environments can promote informal work discussions.[462] Furthermore, since several microforest space types were found to be preferred for a diverse range of work tasks and programs, workspaces within microforests can be more easily repurposed if their current program is not being utilized by the occupants, or when the program needs of the building occupants change. Since occupant program and space needs are dynamic, and office building occupants themselves change over time, the adaptability of microforests is therefore a valuable asset. Thus, building program spaces can be incorporated into the design of microforests, which can increase the effectiveness and efficiency of the building, as well as office space use rates.

§ 3.5 Building resource consumption rates *(Microforest as building infrastructure)*

When integrated into the design of building spaces and systems, microforests can help reduce the resource consumption rates of building projects, through a diverse range of physiological and psychological design strategies. These performance based design strategies can generate substantial reductions in building operating costs, as discussed in Chapter 4.

Moreover, vegetation can be designed to be integrated into multiple building systems, as well as provide multiple performance benefits. For instance, interior vegetation can help filter rainwater, greywater, and/or blackwater, while at the same time, filter air, store water, function as thermal mass, and produce commercial plants, among other potential performance benefits.[222, 345, 480] These integrated design approaches increase the effectiveness of microforests and reduce building operation costs.

As discussed in Chapter 2, an in-depth analysis of the diverse ways that microforests can reduce building and occupant resource consumption is outside the scope of this book. Furthermore, a review of existing literature and discussions with engineers, developers, and building clients indicated that, in terms of reducing a building's operating costs via reducing the rate of resource consumption of a building, design to reduce the energy consumption rates of buildings is currently more effective than reducing water and solid waste consumption rates. This is partly due to the undervaluation of the total economic costs of water, solid waste, and electricity to local and global societies, as discussed in Chapter 2. Nevertheless, due to this research finding, the studies of this research project that explored the potential of microforests to reduce the resource consumption rates of buildings were focused on reducing their energy consumption rates. Furthermore, Chapter 9 presents a myriad of psychological design strategies that can be effective at reducing the resource consumption of building occupants.

§ 3.5.1 Building energy consumption rates

The various ways in which microforests can be designed to reduce the energy consumption rates of building projects can be organized into two general design strategies: physiological and psychological design strategies. In order to evaluate the performance potential of both strategies, several studies were conducted: an exploratory design research case study, which is discussed in Chapter 4, as well as a thermal comfort quasi-experiment, which is discussed in Chapter 5. These studies employed different research methodologies, in order to investigate and evaluate a wide array of potential methods and opportunities that microforests can reduce the energy consumption rates of building projects.

For instance, the exploratory design research case study evaluated the potential influence of plants on building energy use at the individual space scale, and compared these benefits to the potential psychological benefits of plants. In contrast, the thermal comfort quasi-experiment investigated the potential effect of plants on occupant thermal comfort, which thereby evaluated one potential means that the psychological benefits of plants may influence building energy consumption rates. The results of these research projects were published in the peer reviewed science journal, Building and Environment, in 2014.[292, 293] These papers are presented in the following two chapters.

Sample of psychological benefits of microforests on building performance

- The design of microforests spaces can reduce building energy use in diverse ways[292, 293]
- Microforests can increase thermal comfort, thereby allowing room temperature setpoints to be raised in summer and lowered in winter[293]
- Microforests can increase space use rates and space efficiency and effectiveness[292, 295]
- Microforests can reduce initial + operating costs of interior vegetation
- Plants can reduce lighting use + visual discomfort[204]
- Microforests can improve worker performance and well-being at the same time *(discussed more in Chapter 6)*

§ 3.6 Chapter Conclusion

Thus, it is evident that there is substantial potential for microforests to reduce the construction and operating costs of building projects, as well as building resource consumption rates, through a diverse range of design strategies and solutions. For instance, microforests can be more cost effective than more typical interior vegetation solutions, while also providing a number of benefits to building occupants. The potential building performance benefits of microforests, and their interrelationships with various worker performance parameters, are summarized in Figure 3.1.

Moreover, it is important to consider that building performance is inherently interrelated to the social and ecological performance of building projects as discussed in Chapters 4, 5, 6, 7, 9, 10, 11, and 12. To this end, the following chapters explore diverse ways in which microforests can improve the building, worker, and ecological performance of buildings, as well as investigate inherent interrelationships between these three performance categories and specific performance parameters.

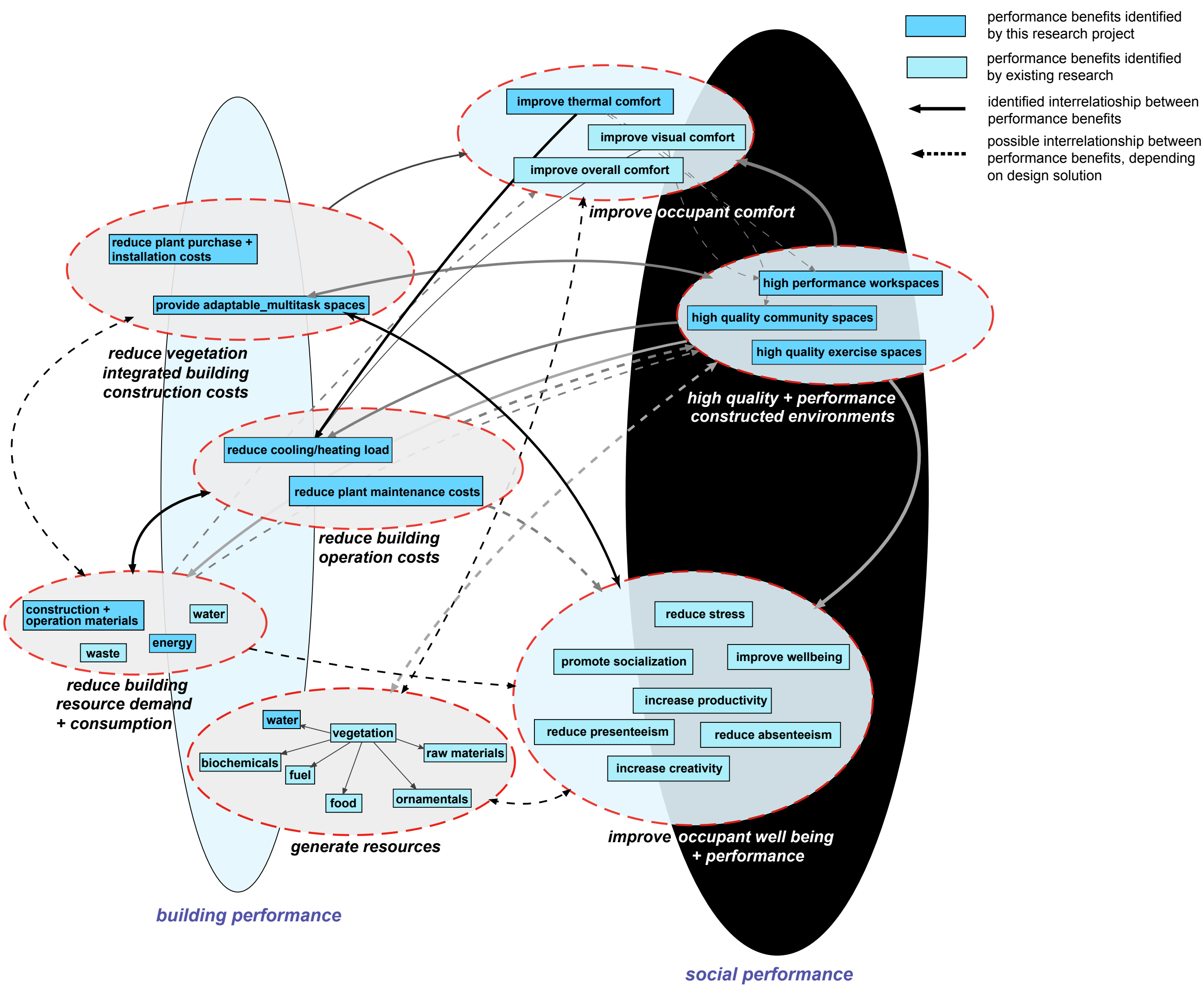

FIGURE 3.1 Potential microforest building performance benefits, and their interrelationships with worker performance benefits

4 Forest Microclimates

Investigating the performance potential of vegetation at the building space scale

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Abstract

The aim of this chapter is to identify and evaluate the potential impact that the incorporation of vegetation into the building design process can have on building energy use and worker performance parameters. To this end, the effect of a vegetation shade canopy on the energy consumption rate and carbon emissions of an 11,000 m² office building, as well as the canopy's potential effects on worker performance, were evaluated. The vegetation canopy's performance was compared to the performance of a typical shading device. The performance evaluations were developed through the use of a dynamic energy modelling program, as well as through an evaluation of the potential building and worker performance benefits of vegetation that have been assessed in existing literature.

The thermal effects of the vegetation canopy were found to have a slightly greater effectiveness than the original shading solution. However, the additional performance benefits gained from integrating vegetation into the occupants' experience of their work environment were found to generate substantially greater revenue. In addition, the occupancy of the vegetated courtyard was found to be more effective at reducing the energy consumption and carbon emissions of the building than the vegetation shade canopy. These results indicate that the development of high quality, high performing spaces that attract building occupants can be more effective design solutions at the individual building space scale, in terms of energy consumption, company revenue, and worker performance and well-being.

Keywords: vegetation; shading; energy use; productivity; thermal comfort; forest microclimate

§ 4.1 Introduction

§ 4.1.1 Background

As existing research has shown, the integration of vegetation into the design of building environments in existing building renovations and new building constructions can improve the performance of buildings and occupants in regards to a wide range of performance parameters. For instance, extant research indicates that vegetation design strategies can result in significant reductions in building energy use, operation costs, and resource consumption, while improving building air quality, occupant comfort and well-being, space utilization and efficiency rates, employee absence rates, creativity, productivity, and company revenue.[199, 241, 358, 418] Historically, vegetation has been utilized to moderate the microclimate of buildings, from channelling wind through Roman Villas for natural ventilation to utilizing climber plants and deciduous trees to shade exterior facades and cool courtyards in various cultures and contexts throughout the world.[8, 218] Furthermore, diverse vegetated environments have been integrated into buildings to improve occupant performance, comfort, and well-being, through a variety of design solutions and strategies. For example, they have functioned as restorative environments in the arcades and courtyards of villas, palaces, and public buildings for centuries, from ancient Chinese and Japanese gardens, to medicinal and agricultural gardens in European monasteries, to healing gardens in contemporary hospitals.[4]

Paradoxically, the potential performance benefits of integrating vegetation into the built environment have not yet been rigorously quantified and qualified, and are currently relegated to generalizations and assumptions. For instance, in a study by The Netherlands Organisation for Applied Scientific Research (TNO), vegetation increased creative productivity by 11%, and by 34.7% if the person was stressed. Roger Ulrich, on the other hand, found a 30% increase in the creativity of occupants.[228] However, the results of these studies do not indicate the effects of various design parameters on worker creativity, such as the effect of different plant quantities and types of personal interactions with plants. Due to these limitations, design teams are currently unable to accurately account for the benefits of vegetation in their performance calculations, building system designs, and development and comparison of various design solutions. This, in turn, limits the incorporation of plants into building environments, and substantially diminishes the potential of building environments, systems, and occupants to benefit from the diverse range of performance benefits that existing research indicates vegetation can provide.

§ 4.1.2 Research objectives and approach

Thus, the objective of the research project presented in this chapter was to identify and evaluate the potential building and worker performance benefits that can be generated by integrating vegetation into the design of buildings and building spaces. This objective is addressed through a review of existing research, and the evaluation of a case study project. Specifically, the performance potential of a vegetation shade canopy is evaluated, through simulations and performance evaluations based on analysis and application of existing research findings from a variety of research domains. Furthermore, the physiological and psychological performance benefits of vegetation that have been identified and evaluated in existing research are presented and discussed, gaps in existing research and future research opportunities are identified, and the current limitations of evaluating the impact of vegetation on various building and worker performance parameters are discussed.

This evaluation process resulted in the identification of innovative ways in which the incorporation of vegetation into the design process, and the design of building spaces in general, can substantially impact building and worker performance. Thus, this research project and evaluation process investigates the potential symbiotic interrelationships that vegetation can generate between the thermal and energy performance of the built environment and occupant thermal comfort, well-being, and productivity.

§ 4.2 Vegetation performance parameters

§ 4.2.1 Vegetation psychological performance parameters

Existing research indicates that vegetation has a positive impact on a broad range of worker performance parameters. For example, several researchers have found that vegetation improves worker productivity by 10 – 15%.[278, 298] As discussed in Section 1.1, plants have been found to improve worker creativity between 11.0 and 34.7%.[228] In addition, vegetation has also been found to improve occupant comfort, as well as their perception of the quality of their environment, including greater acoustics, air quality, and visual comfort and light levels.[45, 146, 423] However, the existing research in this research domain generally does not account for the influence of the degree of personal interaction with vegetation on these performance parameters.

To this end, existing research findings, such as in Kahn et al. (2008) and Adevi & Martesson (2013), indicate that direct, personal interactions with nature in a spatial environment, such as gardening and reading a book under a tree, are more beneficial and effective than indirect interactions, such as passing by a green wall while walking down a hallway, in regards to a variety of performance parameters.[4, 233] These findings indicate that natural environments are more beneficial to the comfort, well-being, and performance of workers than less interactive and immersive vegetation design solutions, such as green walls and roofs that do not directly engage building occupants.

Furthermore, research in the field of restorative environments provides further insights into the benefits of direct interactions with natural environments. Restorative environments reduce occupant stress by snapping one out of direct attention, and providing fascinating stimuli in a coherent manner.[241, 418] In addition, restorative environments have been found to provide a diverse range of performance benefits. For instance, the development of restorative environments can improve the perceived quality, usefulness, and therefore occupation of the space.[241, 418] This is partly because these environments are perceived by occupants as high quality, restorative, stress reducing, and compatible with occupants' needs. In addition, restorative environments have been found to improve individual's mental and physical health, illness recovery time, as well as improve worker productivity and creativity. In addition, the occupation of restorative environments has been found to reduce worker absenteeism and lead to individuals engaging in new mental, social and physical health programs, such as losing weight, music lessons, and volunteer work, which in turn increase company efficiency and profits.[49, 241, 418] Interestingly, natural environments have been found to be highly restorative. Unfortunately, restorative environments have also been found to be substantially lacking in urban environments throughout the world, and yet are heavily desired by building occupants.[418]

§ 4.2.2 Vegetation physiological performance parameters

§ 4.2.2.1 Identifying vegetation physiological performance parameters and application limitations

In terms of the thermal performance of vegetation, general estimations for shading performance, insulation potential, evapotranspiration rates, and soil thermal mass have been developed, as well as case studies on the effect of vegetation on interior room and wall assembly temperatures and energy consumption.[141, 227, 358, 400] Perez et al. (2011) provides a detailed literature review of the existing research findings on the thermal performance of vegetation.[358] These research findings have been evaluated for different vegetation building applications at different levels of rigor, such as green roofs, green walls, vegetation functioning as blinds within window assemblies , and plants as wind barriers and shading devices.[358] For example, Sailor (2008) developed a green roof model for building energy simulation programs that was empirically evaluated through comparisons with measurements of several different green roof integrated buildings, each in different locations with different climates. However, this model cannot currently be applied to evaluating alternate vegetation design solutions, such as vegetation shading structures, and cannot evaluate the performance of certain design variables, such as vegetation more than one meter tall.[388] The performance of various vegetation types, functions, and building applications, such as vegetation shade structures, have not yet been adequately integrated into commercially available energy modelling programs.

These issues make it difficult to evaluate and compare the performance of various vegetation design solutions. This, in turn, limits the use of vegetation to improve the building performance of building projects, by limiting the ability of design teams to account for the benefits of vegetation in their performance calculations, building system designs, and development and comparison of various design solutions.

§ 4.2.2.2 Identifying vegetation shade structures' physiological performance based application potential

Nevertheless, it is possible to evaluate the potential thermal performance of vegetation in building projects, by investigating the application potential of the performance benefits of vegetation that have been found in existing research. For example, research indicates that vegetation walls, in which vegetation is either attached to or directly adjacent to external building surfaces, are more effective at reducing building heating and cooling loads than vegetation shading strategies, such as building adjacent trees and vegetation integrated shading devices.

Vegetation walls have been found to generate a buffer microclimate between the vegetation and wall surface. This microclimate is partially a consequence of the shading and evapotranspiration effects of plants, as well as their composite function as a wind buffer. These functions result in the development of a relatively stagnant air layer between the vegetation and adjacent wall, which provides an insulation effect. The stagnant air layers and buffer microclimate zones created by vegetation walls reduce the rate of heat transfer between the exterior and interior of external wall assemblies.[135, 359] The insulation potential of vegetation walls is considerable. Vegetation walls have been found to reduce peak summer cooling loads by as much as 28%, as well as provide approximately 5 °C of insulation in extreme winter conditions.[119, 358] Perrini et al. (2011) suggests an optimal air cavity thickness of approximately 40-60 mm.[359] However, air cavities between vegetation and exterior walls of 20.0 cm or more have been found to be ineffective at functioning as a stagnant air layer, thereby not providing the previously discussed insulation benefits.[359] In addition, the effect of vegetation on outdoor air temperature has been found to be minimal at distances of one meter and more from the vegetation layer, with some experiments indicating a negligible effect of plants on outdoor air temperature begins at 10.0 cm from the vegetation layer.[359]

Since vegetation shade structures do not create buffer microclimate zones between the window and the external environment, and their effect on outdoor air temperature is minimal, the contribution of the evapotranspiration rate, wind barrier effects, and insulation effects of vegetation to the energy performance of the building can be expected to be less important than in vegetation wall scenarios, depending on the design solution. However, vegetation walls can be problematic for glazed wall assemblies, because the vegetation can limit interior daylight access and occupant views to the exterior, obstruct the function of operable windows, and require additional building maintenance to preserve views, and in some situations, to repair vegetation damage to window and wall assemblies, depending on the vegetation species and design solution.[349] In these situations, external window shade devices can be an efficient and effective solution. Vegetation shade strategies can offer considerable benefits for these types of design situations, compared to typical shading devices. For instance, the temperatures of vegetation leaves typically do not become more than 40-45 °C, although higher temperatures have been recorded in extreme conditions such as deserts. In contrast, metal surfaces and solar cells have been found to reach 80 °C or more.[205] Depending on the design, vegetation shading devices can also provide social, psychological, and ecological benefits. Furthermore, at the building scale, shading devices can be a more feasible financial design solution to improve building energy use, compared to covering all the external walls with vegetation. A combination of both methods may also be an effective solution, depending on the project goals, constraints, and context.

The application of these research findings can provide evaluations of the performance potential of various vegetation design strategies, and be utilized to identify potential high performing design solutions.

§ 4.3 Methodology

§ 4.3.1 Building project description

The case study building presented in this chapter is an 11,000 m^2 new construction commercial office building situated in Accra, Ghana. Accra has a tropical climate with relatively low diurnal temperature swings and moderately consistent temperatures throughout the year. Buildings within this climate must be cooled throughout the year, in order for occupants to feel thermally comfortable. Passive strategies, such as natural ventilation, can be used in place of mechanical cooling strategies during the average thermal day. Dehumidification is required, in order to prevent damage to the electronic equipment, during the operating hours of extreme thermal days, and is necessary for a small percentage of operating hours during average thermal days. The winds contain a significant quantity of sand particulates, leading to potential air quality issues with interior open air courtyards and direct natural ventilation strategies.

The work spaces are elevated above the ground floor, allowing for a 768 m^2 open air vegetated courtyard space on the ground floor, which is illustrated in Figures 1-3. The courtyard space has been designed to be utilized as an informal meeting space and restorative environment, through the incorporation of vegetation and other natural elements. The building facades adjacent to the courtyard are comprised of external double glazed curtain wall assemblies. The original shading structure for these glazed facades was an external building façade shade system. This shade system consisted of an exterior metal perforated fixed panel shade system, which shaded approximately 80% of the glazed surface area, as illustrated in Figures 2 and 4 (b). This shade system was also specified for the external building façade that faces the perimeter of the site, as illustrated in Figure 1.

FIGURE 4.1 External office building façade depicting metal façade shade strategy

FIGURE 4.2 Courtyard space illustration depicting metal and vegetation shade strategies

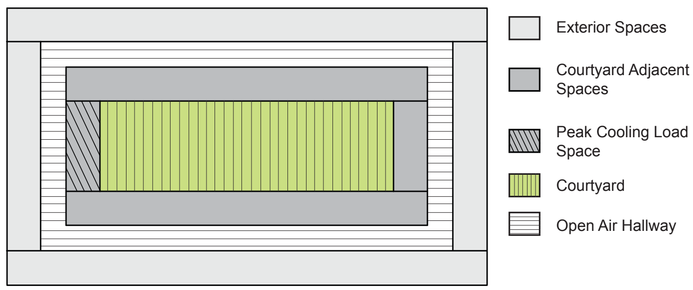

FIGURE 4.3 First floor plan general space layout

The design intent of the architect was to create a low energy, climate responsive, high quality office environment for the building owner and occupants. The engineer was focused on developing a reliable, high performance mechanical system for the building. The realization of the initial design concept became problematic during the course of the development of the project, due to the high cost of the initial perforated metal screen shading strategy and courtyard adjacent exterior wall assemblies. A vegetation shading canopy over the courtyard was explored as a potential cost effective shading solution alternative for the courtyard adjacent metal screens. Both shading solutions are illustrated in Figure 2. The vegetation canopy is composed of creeper vines that are grown along stainless steel suspension cables, which are affixed to the building structure via steel tension cable rods. These vegetated cables span the courtyard opening, effectively shading the courtyard space and adjacent building façades, as shown in Figure 4(c).

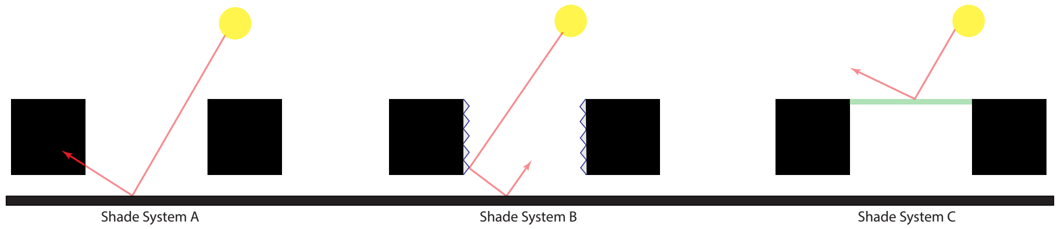

FIGURE 4.4 **(a)** No courtyard shade **(b)** Courtyard metal wall shade **(c)** Courtyard vegetation canopy shade

§ 4.3.2 General research project description

The shading effect of the suspended vegetation canopy, and the original shade structure, on building energy use and carbon emissions were evaluated. A vegetation shade canopy was used as the vegetation design space type to incorporate into the case study because the analysis of existing research indicated that it has substantial potential to improve building energy consumption rates and worker performance, while also providing a range of other performance benefits that other, more typical, building integrated vegetation solutions could not provide. For instance, during the course of the design process, it was determined that the vegetation canopy provided an opportunity for occupants to interact with nature, indirectly by viewing the canopy from the courtyard adjacent facades, and directly through interaction with the canopy when occupying the semi-outdoor courtyard space. As previously discussed in Section 2.1, existing research indicates that these interactions can provide additional benefits to the building occupants. In addition, the shading canopy would shade the courtyard space, thereby increasing the occupancy potential of the courtyard, and potentially reducing building heating and cooling loads, by reducing the solar radiation absorption potential of the courtyard and the temperature of the air within the courtyard.

Therefore, shading design solutions can potentially improve the performance of adjacent spaces, thereby further improving the performance potential of the shading device. This premise was tested by evaluating the performance of the courtyard space with and without the vegetation shading canopy. In addition, the impact of the suspended vegetation and courtyard space on worker productivity, well-being, and comfort, was estimated, based on existing research results. This multi-parameter performance evaluation was developed in order to determine the potential effects of vegetation shading devices and vegetation integrated spaces on building and worker performance, as well as to compare their performance to the performance of typical shading devices. By incorporating existing research findings into the design process, and comparatively evaluating the performance of various design solutions in regards to a variety of performance parameters, the relative value of the different performance parameters, their potential positive and negative interrelationships, and the resulting overall performance of the design solutions are identified and evaluated.

§ 4.3.3 Simulation methodology

The potential energy performance benefits of the vegetation canopy shading device were evaluated through the use of Integrated Environmental Solutions (IES), a dynamic energy modelling and building performance analysis program.[24] IES incorporates a dynamic thermal simulation program, named ApacheSim, into its application suite. It's accuracy has been evaluated by "a number of analytical verification, empirical validation, and comparative testing studies",[14, p.34] by undergoing the ANSI/ASHRAE Standard 140 accreditation process. ApacheSim has also been qualified as a Dynamic Model in the CIBSE system of model classification.[107] The various performance capabilities of IES, in comparison to other energy modelling programs, have been documented by Crawley et al.[108]

In order to measure the potential energy performance benefits of the vegetation canopy shading device, five energy model scenarios were evaluated for the shading of the courtyard space and adjacent exterior wall assemblies. Two energy model scenarios were evaluated that did not include the vegetation canopy shading device: the concept building without any shading devices in the interior courtyard (A), and the concept building with the original perforated metal shading strategy (B). These energy model scenarios are depicted in Figures 4 (a) and (b), respectively. Three energy model scenarios were evaluated that included the vegetation canopy shading device (see Figure 4 (c): the concept building with the vegetation canopy shading strategy (C), as well as shading strategy (C) with 5% of the building occupants occupying the courtyard and their computer workstations turned off (D), and shading strategy (C) with 10% of the occupants occupying the courtyard and their computer workstations turned off (E). The comparison of shading strategies (A), (B), and (C) allows for the evaluation of the effectiveness of a shading canopy to reduce building heating and cooling loads, compared to providing shading devices along the total exterior wall surfaces adjacent to the courtyard area. The comparative evaluation of shading strategies(C), (D), and (E) assesses the potential effects of occupant behaviour on building performance.

The influence of the various shading strategies on the building's thermal performance were investigated through the calculation of the following performance metrics:

- *Mechanical System and Equipment Annual Carbon Emissions*
- *Mechanical System and Equipment Annual Energy Consumption*
- *Air Conditioned Space Peak Cooling Loads*
- *Annual Thermally Comfortable Operating Hours of the Courtyard Space*
- *Operative Temperature of Courtyard Space*

The building site was not influenced by the shadow projections from the adjacent buildings, due to their relative distance from the building site. Therefore, the surrounding building objects were not incorporated into the energy model scenarios. The water features and plants that are illustrated in Figures 1 and 2 were also not incorporated into the energy model scenarios, with the exception of the plants in the roof level vegetation shading canopy that are illustrated in Figures 2 and 4 (c). This is because the thermal effects of these elements were not the main focus of the experiment. The courtyard floor material was defined as the same exterior concrete floor assembly as the ground floor of the rest of the building.

The design of the building, building climate system, and project material specifications were still under development during the course of the research project. Therefore, the building design, climate system, and building materials that were being considered at the time of this research project were used for the specifications for the energy model calculations (see Table 4.1). It is important to note that the reported specifications may not accurately reflect the specifications used in the finalized NLC building project. Nevertheless, the potential differences between the reported and final specifications of the climate system and building design will not significantly affect the energy performance of the building, because suitable alternate climate systems will have comparable specifications. Furthermore, since the goal of the research project is to compare the effect of different shading strategies on the energy demand of the building, the quantitative effect of the shading strategies will not be affected if an alternate climate system is incorporated into the final project specifications.

The climate system that was specified for the offices consisted of a VAV dual duct system that incorporated mechanical ventilation of outside air and a centralized control system. The nominal Coefficient of Performance (COP) of the mechanical system was 3.13. The estimated air infiltration rate for the building was 0.04 cfm/ft^2. Operable windows were being considered at the time of the research project, but due to potential dust issues and construction costs, they were not specified at the time of the research project. Lighting loads, body heat gain, and computer loads were incorporated into the energy model, as illustrated in Table 4.1. They were assumed to occur during the operating hours of the office: Monday through Friday from 8:00 to 18:00.

BUILDING COMPONENT	U-VALUE	INTERNAL GAINS	MA XIMUM SENSIBLE GAIN	MAXIMUM LATENT GAIN/POWER CONSUMPTION
Roof Assembly	0.14	Lighting Loads	1.00W/ft^2	1.00 W/ft^2
External Glazing Wall Assemblies	0.35	Body Heat Gain	250 (Btu/h*p)	200 (Btu/h*p)
Interior Partitions	0.28	Computers	1.50 (W/ft^2)	1.50 (W/ft^2)
Internal Ceiling/Floor Assembly	0.23	Air Infiltration Rate	0.04 (cfm/ft2)	
Exterior Floor Assembly	0.05			

TABLE 4.1 Energy model specifications for climate system, building materials, and internal gains

§ 4.3.4 Thermal comfort performance metrics

The operating hours of the office were used to evaluate thermal comfort hours, for an annual total of 2,610 operating hours. The EN15251 adaptive thermal comfort model was determined to be the most suitable for this research project. However, it is important to note that a validated outdoor thermal comfort model that is accurate for Accra, Ghana has not yet been developed. The local climate and culture, design character of the space, as well as psychological and physiological influences on the thermal comfort of people in Ghana have not yet been determined.[335, 340, 459]

Predicted mean vote (PMV) and physiologically equivalent temperature (PET) are commonly utilized in outdoor thermal comfort analysis. However, these thermal comfort models have been found to be significantly inaccurate and generate overly restrictive results. This is partly because PMV and PET are unable to fully account for psychological adaptation parameters.[302, 459] For example, existing research has determined that people feel thermally comfortable in wider temperature ranges in exterior environments than interior environments, because they feel they do not have control over the factors that determine the thermal environment in exterior spaces.[415] For instance, individuals cannot control when the sun is shining and the wind levels increase.

Recent research projects have generated promising results through calculation methods, such as thermal comfort models in Europe that incorporate the Actual Sensation Vote (ASV), and localized outdoor thermal comfort models in the US.[340, 434] However, these models have not been investigated for a climate and culture similar to Accra, Ghana. The European EN15251 adaptive thermal comfort model was developed for interior environments, and has its own shortcomings, such as potentially being over restrictive in outdoor environments. Nevertheless, it has been found by previous researchers to be less restrictive and more accurate for outdoor environments than the PMV and PET models.[337] The scope of this research project is a comparative analysis, and therefore this method is sufficient to discern the discrepancies in thermal performance between the various shading strategies.

§ 4.3.5 Vegetation shading performance metrics

The shading potential of vegetation can be referred to as its porosity ratio, which is the equivalent of an object's solar transmission ratio (the quantity of solar radiation that is transmitted through an object/total solar incident radiation that falls on the object). Although vegetation admits variable levels of radiation in different areas of the vegetation surface due to variable leaf density, leaf area index, etc., existing research indicates that various plant species and tree canopies can reflect and absorb between 80% and 95% of solar incident radiation.[141, 218, 345, 400] It is important to note that in plant canopy areas where leaf density is quite low, the porosity ratio can be considerably higher. One study found that areas of single layer leaf density reduced solar radiation transmission through the plant by 37%, although this rate also depended on plant type.[358] Nevertheless, the purpose of this study is to determine the potential of established plants, thus the porosity ratio of high leaf density plants was used. Thus, a porosity ratio of 20% was utilized in the calculations, in order to determine a conservative estimation of the thermal performance benefits of established vegetation.

§ 4.4 Results and discussion

§ 4.4.1 Building energy performance

The shading effect of the vegetation canopy, shading strategy (C), was found to reduce the annual energy consumption and carbon emissions of the building's mechanical system by 2.9%, compared to shading strategy (A). Shading strategy (C) was 0.9% more effective than the metal shade system, in comparison to the energy consumption and carbon emissions of the buildings mechanical system in the shading strategy A energy model scenario (see Table 4.2 and Figures 4.5 and 4.6). It is important to note that a plant shading strategy with a lower porosity ratio, which has been found in research and practice, will contribute to greater energy savings and carbon emissions.[141, 218] These results indicate that shading canopy strategies can be more effective at reducing building energy consumption than shading complete external wall assemblies in interior courtyard environments, and that vegetation can function effectively as building shading devices.

Building Energy Consumption + Carbon Emissions	Shade A	Shade B	% B/A	Shade C	% C/A
Annual Mech. System Energy Consumption *[Mbtu]*	2,858.4	2,801.2	2.0	2,775.5	2.9
Annual Equipment Energy Consumption *[Mbtu]*	684.5	684.5	0.0	684.5	0.0
Annual Mech. System Carbon emissions *[lb CO_2]*	954,805	935,718	2.0	927,109	2.9
Annual Equipment Carbon emissions *[lb CO_2]*	228,637	228,637	0.0	228,637	0.0

TABLE 4.2 Annual building mechanical system and equipment energy consumption and carbon emission rates, based on courtyard variant shading strategies

The contribution of occupants and their computer workstations to the internal heat gains and energy consumption of the air conditioned spaces will be reduced when occupants inhabit the courtyard space, as previously defined in Section 3.3. If 5% of the occupants temporarily inhabit the courtyard at any given time during the operating hours of the office, the annual energy consumption and carbon emissions of the building mechanical system will be reduced by 3.8%, compared to the performance of the building mechanical system using shading strategy (A). The annual equipment energy consumption and carbon emissions will be reduced by 4.8% and 4.7%, respectively (see Table 4.3 and Figures 4.5 and 4.6). If 10% of the occupants inhabit the courtyard, the annual energy consumption and carbon emissions of the building mechanical system will be reduced by 4.8%, compared to shading strategy A. The annual equipment energy consumption and carbon emissions will both be reduced by 9.5% (see Table 4.3 and Figures 4.5 and 4.6). Therefore, the inhabitation of 10% of occupants in the courtyard is substantially more effective at reducing the energy consumption and carbon emissions of the building than the shading of the internal courtyard. These results indicate that the development of high quality, high performing spaces that attract building occupants can be more effective than shading strategies at the individual building space scale, in terms of reducing building energy consumption and carbon emissions.

Building Energy Consumption + Carbon Emissions	Shade D	% D/A	Shade E	% E/A
Annual Mech. System Energy Consumption *[Mbtu]*	2,749.7	3.8	2,722.3	4.8
Annual Equipment Energy Consumption *[Mbtu]*	652.0	4.8	619.6	9.5
Annual Mech. System Carbon emissions *[lb CO_2]*	918,518	3.8	909,360	4.8
Annual Equipment Carbon emissions *[lb CO_2]*	217,809	4.7	206,976	9.5

TABLE 4.3 Annual building mechanical system and equipment energy consumption and carbon emission rates, incorporating dynamic courtyard occupancy rates

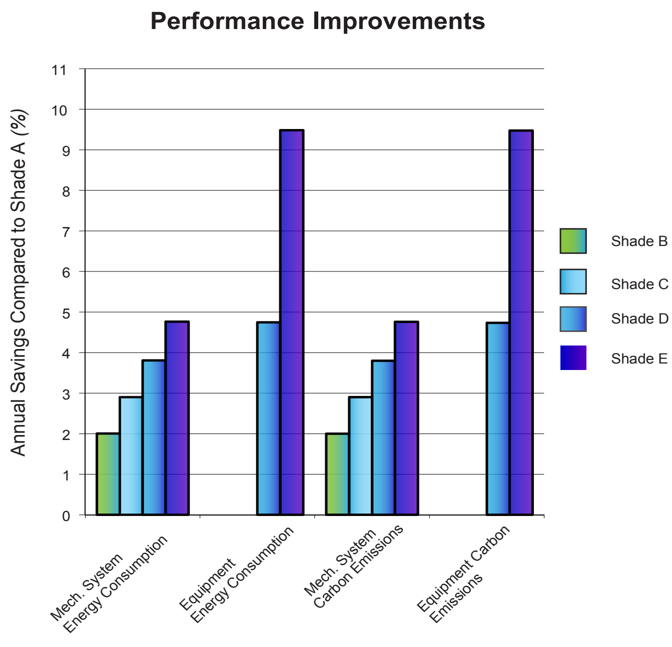

FIGURE 4.5 Annual Energy Consumption and Carbon Emission Savings of Shading Strategies

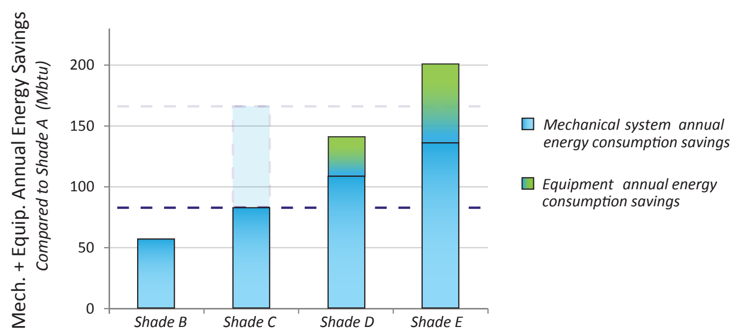

FIGURE 4.6 Annual Energy Consumption Savings of Shading Strategies

As shown in Table 4.4, the use of the vegetation shading strategy reduces the peak cooling loads of the air conditioned spaces that are adjacent to the courtyard by an average 21.3%,compared to shading strategy (A). This is a 2.3% reduction in cooling load over the metal shading strategy. When 5% of building occupants occupy the courtyard, the cooling load is reduced by an additional 0.5%. When 10% of building occupants occupy the courtyard, the cooling load is reduced by an additional 1.1%, compared to shading strategy (C).

Peak Cooling Loads [Btu/h*ft^2]	Shade A	Shade B	% B/A	Shade C	% C/A	Shade D	% D/A	Shade E	% E/A
Avg. Courtyard Adjacent Spaces Cooling Load	63.5	51.4	19.0	50.0	21.3	49.6	21.8	49.3	22.4
Peak Space Cooling Load: 1st FL West Interior	67.4	49.8	26.2	49.0	27.3	48.7	27.8	48.3	28.4

TABLE 4.4 Peak cooling loads of courtyard adjacent spaces

It is important to note that the calculations considered the effects of only one or two people not present in each of the individual workspaces that were analyzed, depending on the size of the specific space, in the shade strategies (D) and (E) energy model scenarios. For the purpose of this research project, a conservative number of vacant occupants in individual office spaces were used in the calculations, in order to minimize overestimations of building and space performance of the various design solutions. As demonstrated in the overall building energy consumption and carbon emissions savings generated from shading strategy (D) and (E), the presence of more occupants of specific building spaces in the courtyard, such as during group meetings, can be expected to result in greater space peak cooling load reductions, as well as space energy consumption and carbon emissions savings. Furthermore, the calculated performance benefits of shade strategies (D) and (E) did not include the potential effects of occupant behavior on building lighting, plug loads, and occupant dependent HVAC loads. Therefore, the building energy reduction potential of the courtyard space is most likely greater than the calculations conducted in this research project.

§ 4.4.2 Semi-outdoor microclimate comfort performance

In terms of the occupancy potential of the courtyard space, shading strategy (C) increases the quantity of annual thermally comfortable operating hours in the courtyard by 9.7%, compared to shading strategy (A) (see Table 4.5). The temperature of the courtyard is also reduced, by a daily operating hour average of 1.1 °C and maximum of 2.0 °C on the peak summer day, and an average 0.5 °C and maximum 1.0 °C during the operating hours of the average summer day (see Figure 7). The metal shade system reflects incident solar radiation into the courtyard space, and allows for the courtyard floor space to receive direct solar radiation. Hence, the quantity of thermally comfortable operating hours and temperature of the courtyard space are not substantially reduced by shading strategy (B), in comparison to shading strategy (A).

Courtyard Space	Shade A	Shade B	Shade C
Annual thermally comfortable operating hours	1358	1366	1612
Percentage of annual operating hours that are thermally comfortable	52.0	52.3	61.8

TABLE 4.5 Annual thermally comfortable hours of the courtyard space

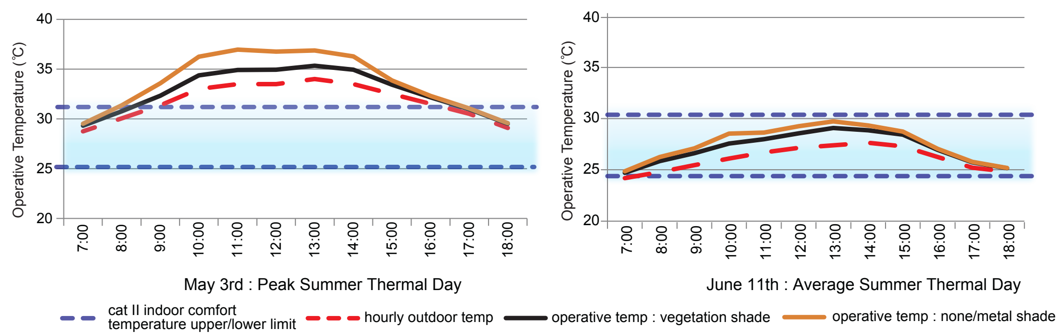

FIGURE 4.7 Courtyard operative temperature and adaptive thermal comfort range

The vegetation canopy also contributes to the overall comfort and well-being of occupants, both psychologically, as described in section 2.1, and physiologically. For instance, the canopy filters harmful air pollutants and inhibits the infiltration of sand particulates into the internal courtyard.[349] Furthermore, it is important to note that although the shading canopy strategy (C) increases the quantity of operating hours the courtyard is thermally comfortable, a substantial quantity of operating hours are still predicted to be thermally uncomfortable (see Table 4.5). As previously discussed in Section 3.4, the EN15251 adaptive thermal comfort model may be overly restrictive for predicting the thermal comfort of occupants of a semi-outdoor courtyard. Regardless, occupants' thermal comfort may be further improved by designing the space to improve their thermal comfort from a psychological perspective. For instance, due to the fact that the thermal comfort range of building occupants expands with increased personal, direct control of their thermal environment, the provision of spatial, vegetated micro climates, such as the courtyard space, may function as a form of spatial thermal control for building occupants.[61] If occupants can view and access a space with a varying micro climate, occupants will be able to spatially control the temperature of their work environment, by circulating between varying micro climate spaces. They may then feel more comfortable in their work space knowing they can move to an alternate thermal condition when they feel uncomfortable. In doing so, the thermal comfort range of occupants may be increased, thereby reducing building cooling loads, by allowing the active conditioning setpoint temperature to be raised in warm weather and lowered in cool weather. Moreover, the quantity of operating hours that are thermally comfortable to inhabit the courtyard may also be increased. However, further research is necessary to evaluate the effect of spatial control on occupant thermal comfort.

§ 4.4.3 Worker performance

As previously discussed in Section 2.1, the design of the shading devices and courtyard spaces can also improve worker performance. Although the specific qualities of restorative environments and vegetation that are necessary to generate the various associated performance benefits have not been identified and evaluated in a manner that allows for a detailed assessment of various design solutions, the potential psychological performance benefits of vegetation can be evaluated by applying the results of existing research findings.

For instance, the courtyard is intended to function as an informal meeting space for occupants, which can increase occupant creativity, collaboration, and well-being, depending on its design and actual use.[69] In addition, the use of a horizontal vegetated canopy above the interior courtyard inherently contributes to the generation of a restorative environment. This is because the vegetation canopy engages the occupants' senses as a source of multivalent stimuli, through the vegetation's intrinsic wind responsive nature, the resultant dynamic shading patterns cast throughout the courtyard and along the adjacent facades, and the thermal cooling effects and improved air quality generated by the natural processes of the suspended vegetation. As previously mentioned in Section 2.1, direct, personal interaction with restorative environments can generate a host of psychological performance benefits. Thus, by designing the courtyard space to function as a sensually responsive, restorative environment, additional benefits for worker performance and well-being can be achieved.

As previously discussed in Section 2.1, research on the impact of vegetation on building occupants has found that worker productivity can be improved by 10 – 15%, although the applicability of these results to various office environment contexts requires further evaluation.[278, 298] However, if the productivity benefits are only 30-50% of the productivity increases found in previous research, which would be a 5 - 10% increase in productivity, the company's annual revenue would be increased by 4.1% - 8.2%. To put this in perspective, a 50% reduction in annual building energy consumption will increase the company's annual revenue by 0.3%. An 80% reduction in energy consumption will generate a 0.48% increase in annual revenue, and if the building becomes energy neutral (100% energy cost reduction), annual revenue will be increased by 0.6%, as illustrated in Figure 8. The annual cost of employee salaries and benefits are, on average, 82.1% of a typical building's annual costs. This is approximately 135 times greater than the annual energy costs of a building.[58] Thus, a 1.0% increase in worker productivity for one year will pay for the building's total energy consumption for 1.35 years. These results beg the question: Can, and should, design teams explore and develop design solutions that improve the energy performance of a building (0.6% of annual building costs), while simultaneously improving the sociological and psychological performance of the environment for the occupants (82.1% of annual building costs)?

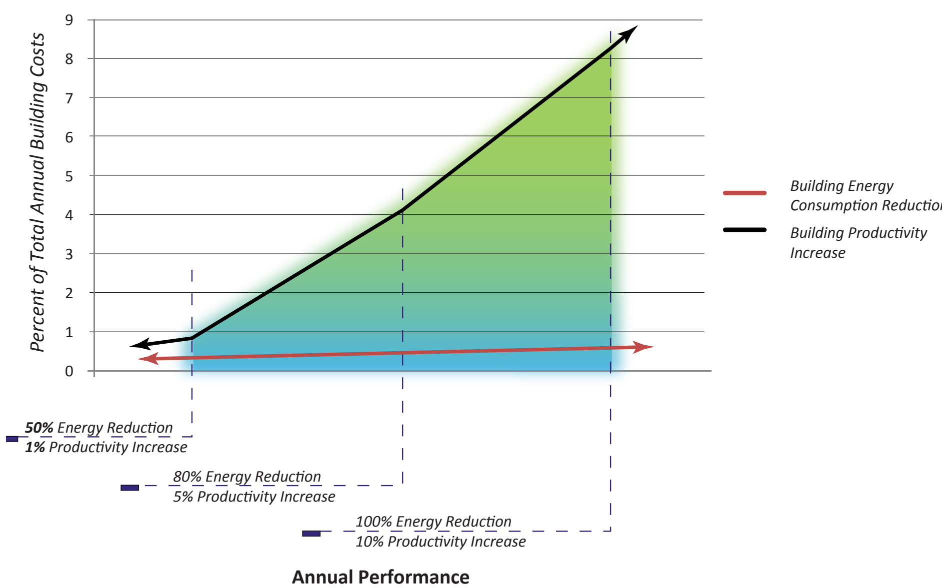

FIGURE 4.8 Annual NLC Energy Consumption Reduction and Building Productivity Increase Rates as a Function of Total Annual Building Costs

§ 4.4.4 Symbiotic building + worker performance potential

The quality of building spaces was found to directly impact the performance, and performance potential, of the building space, building occupants, and overall building. For example, the results that were discussed in Section 4.1 indicate that the more the building occupants inhabit the courtyard space, the greater the reductions in the building's energy consumption and carbon emissions will be. Furthermore, if the courtyard space functions as a high quality meeting space, the quantity of meeting rooms in the actively conditioned portion of the building can be reduced, further reducing energy consumption rates and building costs. To this end, research indicates that the quantity of people that occupy the courtyard, and their frequency of occupation, or space use rate, will increase if they perceive the space as being comfortable, high quality, and compatible with the tasks they want, must, and are able to perform.[49] Thus, the performance of the building space has been directly linked to the quality of the space. The performance of building spaces is therefore partially dependent on the design of the space.

Therefore, more psychological and sociological design parameters should be considered in the building infrastructure design process, in order to improve building performance. For example, addressing occupant behaviour and building facility operations practices has been found to be able to reduce building energy use by approximately 30% in cooling load dominated climates.[203] In addition, research has found that the provision of a high quality view to vegetation, in coordination with the incorporation of daylighting strategies within a building, improve worker evaluation of the quality of their work environment, by as much as 20.5%.[146] High quality views of vegetation, such as viewing the vegetation canopy and courtyard from one's workspace, have been found to improve the occupants' perception of the daylight quality in a building. For instance, when occupants have access to high quality views of vegetation, they perceive lower light levels as adequate for conducting their work tasks. In addition, their sense of discomfort due to glare is reduced.[204] These factors reduce the need for artificial lighting and improve occupant comfort. This, in turn, reduces internal heat load gains and the building's energy consumption. Thus, the provision of high quality views can improve worker comfort and building performance simultaneously.

§ 4.4.5 Symbiotic building, worker + ecological performance potential

The incorporation of vegetation into design solutions has the potential to provide numerous additional benefits for building occupants, building performance, and the local urban ecosystem, compared to typical shading devices. For example, externally located vegetation can reduce local urban heat island effect, thereby providing a climate that is more comparable to adjacent natural ecosystems. This will also inherently improve the thermal comfort of occupants of the surrounding site and the energy performance of adjacent buildings. Furthermore, the canopy can function as a source of habitat for insects, birds, and other flora and fauna, thereby improving the biodiversity and ecological integrity of the local natural ecosystem.[412] The development of vegetation spaces in the built environment thus allows for the potential of generating a distributed or interconnected network of natural, restorative environments that improve the social, economic, and natural performance of the urban environment in a myriad of ways.

§ 4.4.6 Research limitations and future research

§ 4.4.6.1 Vegetation physiological performance benefits application limitations

It is important to note that the physiological performance of the vegetation was not able to be fully taken into account in this research project. This is partly because the performance of various vegetation types and functions have not yet been adequately integrated into commercially available energy modelling programs, or developed to account for specific design parameters, such as the influence of the local air moisture content and plant species. Furthermore, the reliability, methodology, and documentation of important factors that affect a plant's physiological performance, as well as the general applicability of the results of the different research studies, vary. This is due, in part, to vegetation performance depending on a variety of contextual factors, such as irrigation rates, varying growth stages, seasons, local climate conditions, direct and indirect solar radiation levels, and wind speed.[218] In this regard, existing research has evaluated the thermal performance of relatively few vegetation species, and in relatively few climate conditions and seasons.[400] In order for the full range of potential effects of plants on building performance to be considered in the building design process, and be accurately evaluated, further research is necessary to address these issues. For example, the accuracy of the proposed vegetation shading metric could be improved by evaluating the effects of various climates and other contextual factors on the shading potential of various plant species. Furthermore, a standardized methodology to adequately evaluate the performance of various plant species in a diverse range of climates and contexts is also necessary.

For instance, a suitable tool for incorporating the evapotranspiration effects of the vegetation canopy has not yet been integrated into commercially available energy modeling programs. However, as previously discussed in Section 2.2.2, the evapotranspiration of vegetation within a shading canopy will have less of an effect on the cooling and heating loads of the building than vegetation wall strategies. Further research is necessary to determine the evapotranspiration effects of various vegetation shading strategies on building heating and cooling loads, as well as adjacent building spaces.

The effects of air flow through and around vegetation are also currently difficult to accurately assess. Previous research indicates vegetation surfaces and walls with a 20% and higher porosity ratio can considerably decrease wind velocity. These dense vegetation surfaces also introduce additional mechanical turbulence and absorb turbulent kinetic energy, due to their roughness, wind barrier effects, etc.[289, 324] By treating vegetation as a porous shading device in the energy model, the model allowed for air flow around the dense areas of vegetation within the canopy. However, this method did not allow the roughness of the surfaces and edges of the vegetation to be taken into account in the energy model. Several components of the vegetation canopy minimized the importance of these effects in the evaluated design scenarios. For instance, as illustrated in Figures 3 and 4, the canopy is surrounded by the roof of the building. The roof is populated with a diverse array of mechanical equipment, which greatly increases the roughness of the roof surface. The size and roughness of the roof minimizes the effect of the vegetation canopy on local wind flow. Furthermore, as previously discussed in Section 2.2.2, the effects of the vegetation canopy on air flow will be greatest at the canopy level, and rapidly dissipate at a distance of 0.5 - 1.0 m from the vegetation surface. In contrast, the head heights of the occupants of the courtyard will be more than 7.0 m below the canopy. Hence, the local effects of the vegetation on the air flow through the courtyard will not greatly affect the comfort of the occupants. Further research and tool development is necessary to more accurately assess the effects of vegetation on air flow at the building and individual building space scale, and to incorporate these effects into building energy model programs.

§ 4.4.6.2 Vegetation psychological performance benefits application limitations

As briefly mentioned in Sections 1.1 and 2.1, a range of general psychological performance benefits of plants have been identified in existing research. However, the impact of a range of essential design issues, including the quantity, placement, colors, type, and arrangement of vegetation, as well as the degree of interaction between occupants and vegetation, on these performance parameters, has not yet been thoroughly evaluated in these experiments. In addition, the experiments that generated these findings were conducted with various levels of rigor. The same is true of existing research regarding restorative environments. The existing literature in this research domain still lacks the level of detail necessary to allow for the evaluation and comparison of different types and qualities of various restorative environments. Further research should be conducted that addresses the design issues previously mentioned, and to determine the applicability of these findings to a broad range of office and natural environments.

§ 4.4.6.3 Potential impact of occupant behavior on building energy performance

It is important to note that potential reductions in lighting, occupant dependent plug loads, and occupant dependent HVAC loads were not evaluated. However, office building lighting loads represent approximately 39.1% of overall office building energy consumption in the US, while HVAC represents approximately 27.4%, and plug loads approximately 14.8%.[5] Additional energy and carbon savings can therefore be expected from occupants turning off task and potentially overhead lights when they are not in their office, as well as reducing plug loads and HVAC loads. For example, if group workspaces are vacant while a meeting is conducted in the courtyard, the lighting for the group workspace will be unnecessary. In addition, if the heating and cooling setpoints of the workspaces are dependent on occupancy sensors, the HVAC load for the workspace will be temporarily reduced when the workspace is vacant. However, extant research indicates that it is difficult to predict occupant behaviour in these respects, and has been found to be one of the primary reasons for discrepancies between actual building energy consumption rates and predicted energy model calculations.[27] Indeed, simulation models have been found to underestimate occupant energy use, particularly plug loads.[203]

Nevertheless, as buildings become more energy efficient, occupant behaviour dependent energy consumption, such as lighting and plug loads, becomes increasingly important in reducing overall building energy consumption rates.[27] However, further research in predicting the effects of occupant behaviour on building energy and space use is necessary for accurately predicting the potential effects of occupant behaviour on building energy use.

§ 4.4.6.4 Potential barriers for incorporation of vegetation into building projects

In Africa, it has been suggested by local architects, facility managers and building owners, that maintenance of technical systems cannot be guaranteed, as building tenants typically do not maintain the systems. Therefore, design solutions should be designed to be as low maintenance and durable as possible, in order to maintain the effectiveness of the design solution throughout the duration of the building's operation. In addition, during discussions with building facility managers in The Netherlands, some raised concerns that vegetation may attract unwanted microorganisms, insects, and bacteria. However, existing research and discussions with local horticulturalists and zoo habitat managers indicate these potential issues are manageable, and depend on the level of interaction between the plants and exterior environment, the types of plant species that are specified, as well as the plant growth method. Furthermore, potential health issues, such as allergies, are plant specific, and thus can be avoided if they are considered in the design process. The incorporation of vegetation design solutions should also accommodate local building regulations. The building owner and engineers were reluctant to invest in 'unproven' design and system concepts, such as vegetation shading strategies. Specifically, they were concerned about the maintenance and perceived lack of reliability of the growth and shade cover of vegetation on site. The most often cited evidence required to change their opinions was previously built examples. Therefore, further research and development of solutions to these issues will facilitate the integration of vegetation design solutions into building projects.

§ 4.4.6.5 Benefits of further research on potential vegetation performance parameters

The results of this research project indicate that further research into a more diverse array of psychological, physiological, and sociological design parameters can lead to higher performing, higher quality building environments. For example, further research into the performance potential of vegetation could increase the rate of investment in, and development of, vegetation as an effective component of buildings and building climate systems. Further research will make the evaluation and accounting of the performance benefits of vegetation more accessible and clear, and identify and evaluate additional performance benefits. Moreover, existing research suggests that the incorporation of the functions discussed in Section 4.6.1 - 4.6.3 into performance evaluations will result in additional energy savings, depending on the design solution.

§ 4.5 Chapter Conclusion

§ 4.5.1 Conclusion overview

Through the evaluation of the potential performance benefits of incorporating vegetation into building projects as a shading device, a diverse range of performance benefits, as well as high performing design strategies and solutions, were identified and evaluated. An overview of the general conclusions that were developed in this study are outlined and reviewed below.

- *Shading device strategies can be more effective and efficient at reducing building energy consumption than shading complete external wall assemblies in internal courtyard environments*
- *Vegetation shading devices can be as effective, if not more effective, than typical shading devices at reducing solar radiation transmission*

- *A conservative shading metric for evaluating the shading potential of vegetation was proposed (porosity ratio), and the shading performance of vegetation was evaluated and compared to the shading performance of typical shading devices*
- *Vegetation shading devices can provide additional benefits in regards to a variety of performance parameters, in comparison to typical shading devices.*
- *At the scale of an individual building space, the psychological benefits of vegetation can be greater than the physiological benefits of vegetation, in terms of cost and productivity.*
- *Improving worker performance is more important than improving energy performance, in regards to a building's annual costs*
- *The quality of the experience of building spaces directly impacts the performance, and performance potential, of the space*
- *The design and function of building spaces can be more effective at improving the performance of the building and occupants than building shading strategies, at the individual building space scale*
- *Spatial building design and system solutions that are designed to improve a project's performance in multiple performance categories can be significantly more effective than design solutions that are focused on single performance goals*
- *Vegetation can be used to create high quality, high performance spatial environments*

§ 4.5.2 Conclusion elaboration

The shading effect of the vegetation canopy outperformed the metal shading strategy in every measured performance metric. Moreover, the vegetation canopy was found to generate numerous additional performance benefits for the building, the occupants, the local urban context, and the local natural environment, in comparison to typical shading devices. Thus, the vegetation canopy strategy is an effective shading system that provides a diverse range of performance benefits in a broad range of performance categories, and in this specific case study, considerably increases the potential use and intended function of the courtyard.

The case study results, evaluation methods used in this chapter, and discussion of the application potential of existing research into the building design process can aid design teams in determining how and when to incorporate vegetation shading devices and spaces as part of their performance based design solutions, and lead to the identification and development of high performing design solutions. For instance, the vegetation porosity ratio that was proposed in this research project can be incorporated into the design process of future design projects, as an estimation tool to evaluate, and compare, the shading performance of various vegetation design solutions.

In addition, the quality of building spaces was found to directly impact the performance, and performance potential, of the building space, building occupants, and overall building. For instance, the occupation of the courtyard space, and therefore the perceived quality and usefulness of the courtyard space by the occupants, was directly linked to, and improved, the building's thermal, energy, and carbon emissions performance. Thus, the performance of the building space was directly linked to the quality of the design of the space. Therefore, the results of this research project demonstrate that the development of high quality spatial design solutions can improve the performance of buildings and building occupants, depending on the performance parameters that are incorporated in the development and evaluation of the quality of the space, and the effectiveness and efficiency of the solution. To consider this conclusion from another perspective, the occupiable spaces of buildings can function as integrated, high performing components of the building infrastructure, which can be referred to as spatial infrastructure components.

Furthermore, when taking into consideration annual building costs, as well as the energy and productivity benefits of the courtyard space, it becomes clear that spatial building design and system solutions, including spatial infrastructure components, that are designed to improve a project's performance in multiple performance categories, including worker comfort, productivity, and creativity, can be considerably more effective than design solutions that are focused on single performance goals. They can also generate increased annual company revenue, as well as reduce a building's costs and energy use. For example, the integration of the design of the courtyard space into the design of the building's infrastructure systems was found to generate substantially greater energy savings and annual revenue than either shading solution. Furthermore, the courtyard afforded occupants the opportunity to directly interact with a restorative, natural environment, which existing research indicates is more effective than non-interactive design solutions in improving worker performance, comfort, and well-being.

In terms of the potential economic benefits of both the psychological and thermal performance effects of vegetation shading strategies, the psychological benefits, such as productivity increases, have been shown to considerably outweigh the potential thermal benefits of plants, such as plant shading and insulation effects, at the scale of the individual building space. These findings suggest that the quality design of building spaces as part of the building infrastructure system, such as the vegetated courtyard in the NLC building, and their integration into building design, can justify their initial construction costs and lead to significant annual cost savings and improved project performance, in relation to a broad range of performance metrics. Although the quantification of every performance parameter of vegetation has not yet been rigorously developed, the benefits quantified in this chapter significantly surpass the threshold of investment for clients, and merit further investigation.

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5 Constructing Thermal Comfort
Investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment

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Abstract

Several short term studies have found evidence that plants may improve occupant thermal comfort, yet this phenomena has not yet been rigorously evaluated. The aim of this chapter is to present the results of a quasi-experiment that evaluated the effect of indoor plants on the thermal comfort of 67 office workers within an office building in De Lier, The Netherlands, for four months, one month each season, in 2013.

The participants' thermal comfort was recorded twice a day, while the globe temperature, relative humidity, and light levels of the workspaces were monitored. The indoor operative temperature of the test rooms were varied between typical and more extreme indoor operative temperature ranges throughout the quasi-experiment in a controlled manner.

The presence of a substantial quantity of plants in the work environment was found to have a significant effect on the thermal comfort of the participants. For example, the occupants of the two rooms in which the presence of plants was alternated, were both, on average, approximately 12.0% more thermally comfortable when plants were present in the room. In addition, they were approximately 1.79 and 1.95 times more likely to be thermally comfortable when plants were present in the room, respectively.

These results indicate that the incorporation of a substantial quantity of plants in office buildings can lead to reduced building energy consumption and carbon emission rates, by allowing the temperature setpoint to be raised in the summer and lowered in the winter.

Keywords: thermal comfort; vegetation; plants; building performance; worker performance; energy consumption

§ 5.1 Introduction

Numerous research studies have found that plants have a positive impact on people in respect to a diverse range of performance categories. For instance, the presence of attractive vegetation has been found to improve people's general perception of the quality and value of building environments. Plants also have been found to improve people's perception of specific qualities of the indoor environment, such as how relaxing, stressful, noisy, beautiful, and interesting the space is perceived to be.[199, 278, 371, 403, 423, 475] The stress levels, creativity, and productivity rates of office workers have been found to be improved by plants, as well as occupant satisfaction with indoor air quality, glare, light levels, and perceived and physiological overall comfort.[23, 47, 204, 254, 255, 300, 371, 403, 429] However, the effects of plants on occupant thermal comfort have not yet been evaluated in detail.

Several researchers have measured the short term effects of plants on occupant thermal comfort. In one of the more extensive experiments, 30 office workers completed a Subjective Assessment of workplace Productivity (SAP) questionnaire at the end of each workday for two weeks: one week with plants, and one week without plants.[300] This questionnaire included a six point scale to measure occupant thermal comfort. The participants' thermal comfort was found to improve when plants were present in the workplace, although the scale of the effect of plants on thermal comfort was not quantified. However, the majority of existing literature, as well as thermal comfort experiment standards such as the International Standard 10551, use a standardized seven point ASHRAE or Bedford Thermal Comfort Vote scale to evaluate occupant thermal comfort.[220, 336] Moreover, a seven point thermal comfort vote scale, as well as a three point occupant thermal preference vote scale, such as the McIntyre thermal preference scale, have been found to be necessary in accurately assessing occupant thermal comfort by a number of researchers.[15, 213, 312, 336] Furthermore, Matsumoto (2012) did not take into account the potential influence of a variety of influential environment parameters, such as internal and external temperatures, relative humidity, seasons, gender, clothing insulation values, metabolism rates, sunlight, and the short term and long term effect of plants on people.[300]

In a separate study, Mangone et al. (2013) evaluated the thermal comfort of 16 office workers for one month: two weeks without plants and two weeks with plants.[294] The participants' thermal comfort was measured with the seven point ASHRAE Thermal Comfort Vote and McIntyre thermal preference scale measures. The presence of plants was found to improve occupant thermal comfort by 19.0 - 25.0% at typical indoor operative temperature ranges (approximately 22.0° C). At more extreme operative temperatures, the presence of plants was found to improve occupant thermal comfort by at least 35.7%. However, this experiment did not evaluate the effect of potentially influential environmental variables on the participants' thermal comfort, such as possible long term psychological effects of plants, the effect of various seasons, and the influence of plants on different genders. Furthermore, the data analysis in this experiment relied primarily on descriptive analysis, rather than statistical analysis. This limited the ability of the researchers to adequately assess the potential influence of the various measured environmental variables.[294] Thus, further research is necessary to evaluate the potential influence of plants on thermal comfort.

It is important to note that individual thermal comfort has been found to be due, in part, to the influence of psychological parameters. Research indicates that quantifiable, physiological parameters can only account for approximately 50% of the variation between subjective and objective comfort evaluations. This means that up to 50% of people's thermal comfort may be due to the influence of psychological parameters.[415] For instance, occupants' perceived sense of control over their thermal environment has been identified as a key factor for determining one's thermal comfort when inside a building.[61, 116] Occupants' perceived sense of control is used in building thermal comfort standards' as one of the most important factors that determine if a more adaptive thermal comfort model, which requires less energy use, than the more restrictive and typical predictive mean vote (PMV) and predicted percentage dissatisfied (PPD) models, can be used for the design and specification of a building's climate system.[116, 458] Moreover, outdoor thermal comfort models that do not take into account psychological factors have been found to be inadequate for predicting outdoor thermal comfort.[459] In addition, one of the primary reasons for people's outdoor thermal comfort range being wider than their indoor thermal comfort range has been hypothesized to be due to the fact that people assume that the outdoor thermal microclimate cannot be controlled through architectural design or mechanical control, and thus they perceive a broader range of conditions as 'acceptable' in regards to climate.[415] In addition, the results of a large scale survey of buildings in the UK found a correlation of 0.7 between temperature and comfort vote.[305] This is quite high in relation to other surveys where the indoor temperature does not vary too much. This correlation value indicates that 49% of the variation in comfort is due to temperature, which suggests that more than the physical parameters of an environment influence comfort.[336] Furthermore, short term thermal comfort has been found to be affected by people's emotions. For instance, people who feel lonely tend to feel thermally colder.[488] People that have come into contact with someone that feels 'creepy' have been found to feel that the temperature in the room has become colder.[269] These findings indicate that plants can affect people's thermal comfort in several ways. Plants can function as figurative cues, wherein they remind building occupants of outdoor environments, and in doing so, people's thermal comfort range broadens, as if they were outside. Plants can also function as figurative cues in the sense that in the winter, green, living plants might cause people to feel like they are in a warmer environment than they really are, thereby increasing their thermal comfort. In the summer, plants may remind occupants of the cooling effects that a vegetation canopy's shade provides, particularly if there is overhead vegetation. Furthermore, since plants have a positive effect on people's valuation of a space, as previously discussed, then this positive effect of plants may have a larger influence on people's sense of thermal comfort than the negative effect of uncomfortable temperatures. To this end, researchers have found that the presence of plants reduces the negative effects of visual glare and low light levels on office workers.[204]

An in depth analysis of the effect of plants on thermal comfort therefore may lead to the use of plants to improve occupant thermal comfort and broaden the thermal comfort range of building occupants, thereby reducing the energy demands of the building and improving occupant thermal comfort. In addition, the productivity of office workers has previously been found to be diminished when they feel uncomfortably hot.[255, 261, 387] Thus, if plants are found to improve occupant thermal comfort, they may also mitigate the negative effects of uncomfortable temperatures on worker productivity in the process. This chapter describes a yearlong field study that investigated the short term, long term, and seasonal effects of plants on occupant thermal comfort.

§ 5.2 Methodology

§ 5.2.1 Quasi-experiment overview

The effect of plants on occupant thermal comfort was investigated through the development of a quasi-experiment that began in January 2013 and was completed in October 2013. The quasi-experiment took place in an office building in De Lier, The Netherlands. A pilot study was conducted in November 2012 with the participants in one of the test rooms, E1, in order to ensure the effectiveness of the experiment. In general, plants were found to increase the thermal comfort of the participants by approximately 19.0-25.0% in typical indoor operative temperatures. The methodology and results of the pilot study were reported in Mangone (2013).[294]

§ 5.2.2 Experiment methodology design and limitations

Since experiments typically take place in a laboratory environment, they are commonly critiqued, and avoided, by organizational psychologists.[209] This is because the results obtained from laboratory experiments typically are not able to be generalized and applied to real world office environments and employees.[177] For example, a review of existing behavioral research found that students are used in the majority of laboratory experiments, and an analysis of thirty-two published experiments found that the results of laboratory experiments are generally affected by the type of experimental subject, with a number of authors concluding that students were insupportable substitutes for nonstudents.[177] Laboratory experiments are further criticized as having a lack of external validity, because in many cases the research seems to evaluate the ability of the experimenter to produce conditions in the laboratory test environment that show that a clearly true hypothesis is, in fact, true.[311]

An alternative to laboratory experiments are field experiments, which avoid the external validity issues by conducting experiments in real world office environments, and attempt to maintain typical working conditions and environments as much as possible. However, this increased external validity typically reduces some aspects of the experiments' internal validity. For example, it is difficult to randomly assign participants to specific test groups in the field, and even when this is possible, this randomization may affect the validity of the independent variables.[19] For instance, randomly grouping people in teams or workgroups may produce artificial social environments that do not provide the comfort, complementary skills, interpersonal compatibility, and elements of self-selection that are developed in natural team and work group formations.[178] Therefore, these types of experiments are not always appropriate or reliable.

Quasi-experiments can be a suitable alternative in some cases, as they can be developed to have comparably greater external and internal validity, while allowing the random assignment of participants to treatment conditions to be avoided.[178] For instance, quasi-experiments can be designed to identify sleeper effects, which develop when the total impact of a change or manipulation in the experiment is delayed and only becomes evident after a span of time. In addition, quasi-experiments may make these effects more noticeable than in laboratory or true field experiments.[178] There are several reasons for why sleeper effects can occur. The effects of variables may take time to affect the participants, such as distractions or changes in the environment. In addition, short-term responses to a change in the work environment may be different than long-term responses to the same change, due to occupant adjustment processes.[123] A more detailed discussion and analysis of the advantages and disadvantages of using quasi-experiment methods compared to laboratory and true field experiment methods is outside the scope of this chapter. A more extensive review of this topic can be found in Grant (2009).[178]

This research project utilized a quasi-experiment method in order to develop greater external and internal validity than the laboratory and field experiment methodologies. The participants remained in their existing workspaces, and the temperature and presence of plants was changed throughout the quasi-experiment. By alternating the presence of plants in multiple workgroups, maintaining control groups, as well as measuring occupant responses before the presence of plants and after the presence of plants through multiple timespans, the methodology of this research project is considered by behavioral researchers to be one of the strongest possible quasi-experimental designs.[76, 178]

§ 5.2.3 Developed quasi-experiment methodology

§ 5.2.3.1 Quasi-experiment building description

The quasi-experiment was conducted in the 10,000 m^2 Priva Headquarters office building in De Lier, The Netherlands. The Netherlands has a maritime climate, with relatively mild winters, cool summers, high humidity, and precipitation distributed relatively evenly throughout the year. The building was completed in 2008. The building utilizes a mixed mode thermal conditioning system, with operable windows located adjacent to every workspace, and mechanical heating, cooling, and ventilation provided via a chilled beam ceiling system with integrated lighting fixtures. Due to the high insulation value of the building, and internal heat gains, the building was in cooling mode throughout every test period except for the winter test period in January and February 2013. Based on observations during the experiment, and discussions with the facility manager, the building climate system switched from cooling to heating mode when the average outdoor daily temperature was below 5 °C.

The quasi-experiment was conducted in four different rooms on the second floor of the building. Two of the rooms were oriented towards the north, were adjacent to each other, and were physically similar in design and layout. The other two rooms were oriented towards the south, were adjacent to each other, and were physically similar in design and layout. However, D1 was slightly smaller than E1, as it had one less 4 person workspace cluster than E1, as illustrated in Figures 5.3 and 5.2, respectively. All four rooms were similar in design and layout, although all of the workspaces within the south facing rooms face the southern exterior, while half of the workspaces within the north facing rooms face the north exterior and half face the courtyard interior. All views contained visible vegetation. The two southern rooms overlooked the surrounding area, which included several trees, as well as the parking lot of the building, which contained bushes and trees along the perimeter, as well as a few trees within the parking lot. The north facing exterior facades provided views of a nearby Dutch highway, as well as some stands of trees and manicured vegetated landscapes, while the courtyard facing workspaces in the north rooms had views of several trees that were planted in the internal courtyard of the building. The views from the North and South facing façades were composed of roughly the same proportion of vegetation. Regardless of which view the individual workspaces were adjacent to, every perimeter wall in all four rooms had floor to ceiling glazing wall assemblies. The floor to ceiling height of each room was approximately four meters. The workspaces were grouped in 4 person rectangular work groups, with one approximately 1.5m wide desk per person, as illustrated in Figures 5.5(a) and 5.5(b). Each four person cluster of desks had access to an operable window.

67 employees participated in the overall experiment, although five employees moved to other rooms during the course of the experiment. There were approximately 12-16 participants in each room. The number of participants in each room varied depending on the day and season.

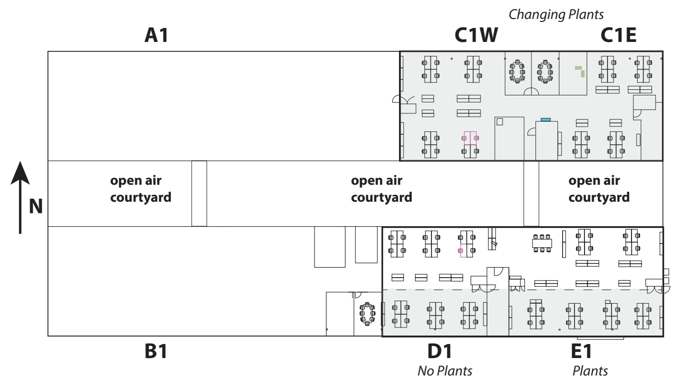

FIGURE 5.1 Overall Priva building room layout and orientation

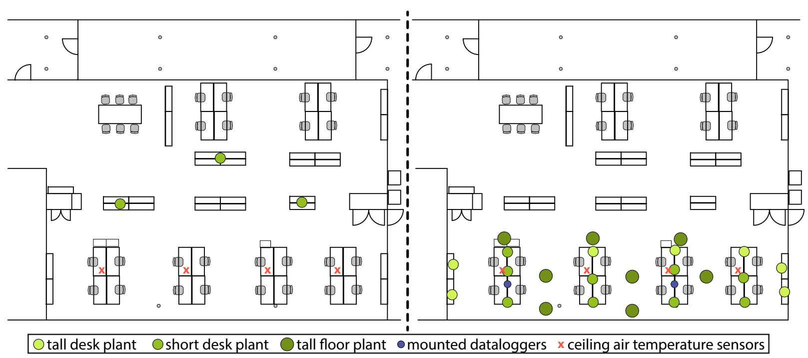

FIGURE 5.2 **(a)** E1 original layout **(b)** E1 experiment layout (with plants)

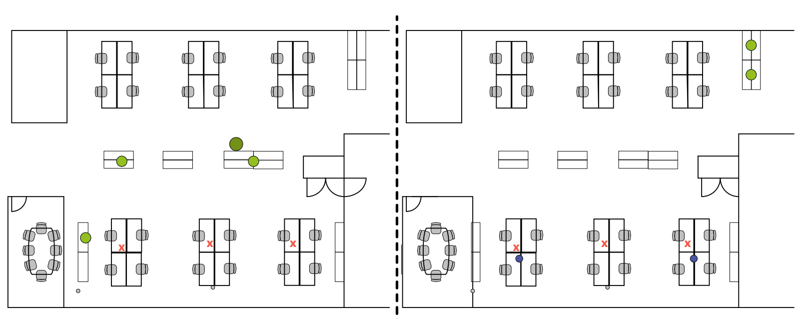

FIGURE 5.3 **(a)** D1 original layout **(b)** D1 experiment layout (without plants)

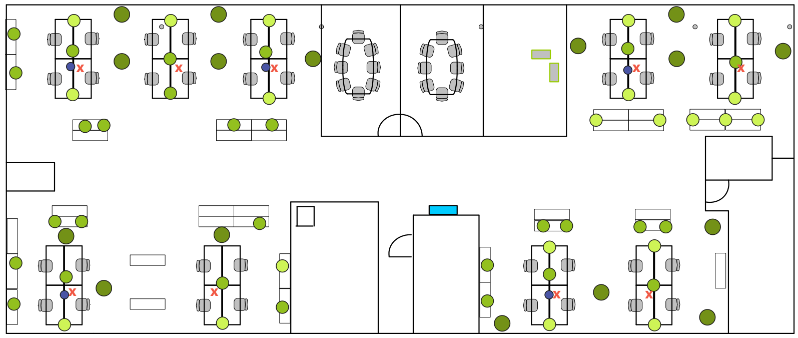

FIGURE 5.4 C1W and C1E layout with plants

 

FIGURE 5.5 **(a)** E1with plants in the room **(b)** D1 without plants in the room

§ 5.2.3.2 Environmental parameter measurement methodology

The interior thermal environment was monitored via HOBO U12-012 dataloggers, which logged globe temperature, relative humidity, and lux at ten minute intervals throughout the test period. The manufacturer reports the accuracy of the temperature measurements to be + 0.35 ºC, and + 2.5% for the RH measurements, for the conditions of the test rooms throughout the quasi-experiment. The accuracy of the dataloggers are within the range required by the NEN-EN-ISO 7726 standard for evaluating thermal environments,[332] as well as those suggested by Nicol (2012).[336] It is important to note that operative temperature in practice has been found to be close to 40mm globe temperature. Furthermore, dataloggers of the same size as the dataloggers used in this quasi-experiment have been found to respond like a globe thermometer, and have been used in their place.[336] Thus, the globe temperatures that were logged by the dataloggers were treated as the operative temperature in the data analysis for this study.

These dataloggers were attached to wood stands via Velcro, which raised the dataloggers to the occupants' seated head height. The dataloggers were then placed in the center of the four desk workspaces, as far away from heat sources and plants as possible**.** In addition, existing thermal sensors in the ceiling measured air temperature, although these were utilized primarily as a reference. This is because the difference in air temperature between the head height of the occupants and the ceiling was found to vary by as much as 1.5˚C throughout the test period.

The air velocity was measured using a Model 9515 VelociCalc Air Velocity Meter, at ten minute intervals for five hours, for three random days throughout each month that the quasi-experiment took place. The manufacturer reports the accuracy of the measurements to be + 0.025 m/s for the range of air velocities that were measured throughout the quasi-experiment. The accuracy of these measurements are within the range required by the NEN-EN-ISO 7726 standard for evaluating thermal environments,[332] as well as those suggested by Nicol (2012).[336] It is important to note that the air velocity did not exceed 0.1 m/s when the windows were closed. The rooms can therefore be assumed to have had little to no air movement when the windows were closed. Moreover, the windows in C1 and E1 were opened infrequently during the summer test session. Regardless, the air velocity did not exceed 0.2 m/s at any of the workspaces during the measurement periods. Therefore, the air velocity within the test rooms was negligible throughout the quasi-experiment. Nevertheless, the opening times of windows were self-reported by occupants in the twice daily questionnaire, and were considered in the data analysis.

The participants' thermal comfort was evaluated via online questionnaires for approximately four weeks each season, for four seasons during 2013. The participants received an email twice a day, at 11:00 and 15:00, during each workday throughout each test period. The emails contained a web link to the online questionnaire, which contained six multiple choice questions about their thermal comfort. The questions recorded the participants' Thermal Comfort Vote *(1 very cold to 7 very hot)*, Thermal Preference Vote *(1 warmer to 3 cooler)*, Moisture Comfort Vote *(1 very dry to 7 very moist)*, Estimated Clothing Insulation Value, Estimated Metabolic Activity for the previous 15 minutes, and whether the closest window to their workspace was open within the last 30-45 minutes.

The standard seven point ASHRAE thermal sensation scale was used for the Thermal Comfort Vote question, and the three point McIntyre thermal preference scale was used for the Thermal Preference Vote question.[336] During the pilot study, multiple participants had verbally reported that the air was sometimes uncomfortably dry, and requested a means to report the dry air in the questionnaire. Hence, a Moisture Comfort Vote was included in the questionnaire. The scale of the Moisture Comfort Vote was based on the ASHRAE Thermal Comfort Vote scale. The ISO 8996 and ISO 9920 thermal comfort standards were used to calculate the supplied ranges and choices of the participants' metabolic rates and clothing insulation values, respectively.

In addition, a comic was included at the end of the questionnaire, in order to promote continued participation. The comic was changed daily. It is worth noting that participants reacted positively to the comics. Sometimes they supplied their own comics, other times they requested different comics, and multiple participants would complain when the comic was not updated by the next day, or when they grew tired of a specific type of comic and desired a new one. The use of comics seemed to improve participation and interest in the quasi-experiment.

The average daily local outdoor temperature, relative humidity, cloud cover, wind speed, and wind direction were recorded from the closest weather station, the Rotterdam Airport Weather station. This station was located approximately 16 km East of the building. The outdoor running mean temperature that was included in the data analysis was the exponentially weighted running mean outdoor temperature used in the European standard EN 15251.[335] This definition has been found to be more accurate than the alternative monthly mean outdoor temperature definition.[59, 335, 336]

§ 5.2.3.3 Defining thermal comfort

Several definitions of thermal comfort can be found in existing literature. For example, a neutral comfort vote on the ASHRAE Thermal Comfort Vote scale (TCV), ie. TCV = 4 (Neutral), has been used to define occupant thermal comfort. However, a number of researchers have found that there tends to be a difference in the definition of thermal comfort among people of different languages and cultures. For example, people from different climates have been found to perceive slightly cool or slightly warm (thermal comfort vote = '3' or '5') as thermally comfortable.[15, 213, 312] In order to correct this issue, some researchers have included a vote of '3' and '5' on the ASHRAE scale as also indicating thermal comfort. However, a number of researchers have found that adding a Thermal Preference Vote (TPV) is necessary to adequately address, and identify, varying people's definition of thermal comfort.[15, 182, 215, 336] In order to take the participants' TPV into account, thermal comfort is defined as slightly warm, neutral, or slightly cool (TCV = '3'-'5'), as well as the participant preferring 'No Temperature Change'(TPV = '2'), Although the third thermal comfort method is considered to be the most accurate, the thermal comfort of the occupants of every room in this quasi-experiment was evaluated according to the three thermal comfort definitions discussed in this section, in order to provide a comparative analysis of the thermal comfort definitions and results of the quasi-experiment. In order to maintain clarity throughout this chapter, the three thermal comfort definitions will be referred to in the following manner throughout the chapter: COMFBOTH will refer to the thermal comfort definition that is defined as a TCV of '3'-'5' and TPV of '2', COMFFEEL will refer to a TCV of '3'-'5', and COMF (4) will refer to TCV = '4'.

§ 5.2.3.4 Thermal comfort logistic regression analysis methodology

Seven potentially influential variables were included in the final logistic regression analysis of the Cl W and Cl E datasets. The variables were chosen based on a literature review conducted by the researchers to identify factors that were found by previous researchers to influence occupants' indoor thermal comfort. The variables that were included in the final logistic regression analysis were the presence of plants, room operative temperature, room relative humidity, participant gender, participant estimated metabolic activity level, participant estimated clothing insulation, and the outdoor running mean temperature. It is important to note that the illumination intensity of the test rooms, measured in lux, the opening of windows, as well as the daily average cloud cover intensity, were also included in the initial logistic regression analysis. However, these three predictors were removed from the final logistic regression analysis because they did not have a significant effect on, and were consistently some of the most insignificant predictors of, occupant thermal comfort, in regards to every thermal comfort model that was developed for every test room. Furthermore, the illumination intensity and cloud cover intensity predictors were also removed from the final logistic regression analyses because they have not been found to considerably influence occupant thermal comfort in existing literature.[142, 336] The participants' responses were grouped and analyzed according to the room each participant occupied. The results of the initial analysis are presented in Tables 5.4, 5.6, 5.8, 5.10, 5.12, and 5.14.

After the thermal comfort models were evaluated via a logistic regression analysis of the seven predictors previously discussed, the data was statistically analyzed via the backward manual elimination method. This further statistical analysis was conducted in order to develop a more parsimonious thermal comfort model. According to this method, after the initial logistic regression analysis is conducted, the most insignificant variable is identified and removed from the analysis. The analysis is then performed again, until all the remaining variables are statistically significant. One exception was made to this methodology, whereby one measurement of temperature, either indoor operative temperature or outdoor running mean temperature, was retained in the analysis regardless of its significance, since temperature has been found to substantially affect thermal comfort in a wide range of existing literature.[336] For example, if the backward manual elimination method eliminated indoor operative temperature as a variable, the variable was removed and the elimination method continued. However, if a later analysis stage identified outdoor running mean temperature as needing to be removed, this temperature variable was not removed. Thus, this further analysis process provided an additional method to evaluate the influence of the various measured variables on the participants' thermal comfort.

§ 5.2.3.5 Temperature range design and control Settings for test rooms

The setpoint for all the test rooms before the quasi-experiment began was 22.0 °C throughout all the seasons. Therefore, the temperature setpoint for the first week of each test period was kept at the pre-existing setpoint for the rooms, in order to evaluate the thermal comfort of the participants at the temperature for which they were accustomed. For each test session, the setpoint of each room was set to the typical setpoint for at least four weeks before the test session, in order to ensure the evaluation of the typical thermal condition of the building, as well as to mitigate potential sleeper effects. After the first week, the setpoint was raised for the cooling load dominated test sessions (April, June, September). This alternate setpoint was maintained for two weeks, in order to measure the thermal comfort of the participants in C1 W and C1 E for one week with plants and one week without plants at the more extreme temperature range. For the final week, the setpoint for all the rooms was returned to the typical setpoint for the rooms, 22.0 °C, as shown in Tables 5.1, 5.2, and 5.3.

During the winter test session in January and February 2013, the setpoint was originally intended to be lowered after the first week. However, when the setpoint was lowered in both rooms in C1, the operative temperature did not decrease lower than the temperature range that occurred at the typical setpoint setting, due to internal heat gain factors and solar gain. Thus, the setpoint in C1 was raised to 23 °C for two weeks during the winter test session, in order to evaluate the effect of plants on occupant thermal comfort at a temperature range that was different from the typical temperature range. The operative temperature in E1 substantially decreased when the setpoint was lowered, and therefore occupant thermal comfort in a lower temperature range was evaluated in E1 during the winter test session, as shown in Table 5.3.

Furthermore, it is important to note that although each room was set to the same setpoint, there was generally a small range in operative temperatures within and between each room, due to variable solar gain, internal heat gains, and occupancy rates of each room, among other typical influential factors. In addition, D1 did not participate in the quasi-experiment until the beginning of the second test session in the spring, so they were not involved in the first test session in the winter.

§ 5.2.3.6 Plant siting methodology

In terms of the presence of plants within the office spaces, E1 and D1 were treated as constant test environments throughout the duration of the quasi-experiment, in order to evaluate the long term effect of plants on occupant thermal comfort. Hence, there were plants present in E1 during the entire quasi-experiment, while D1 did not have any plants present for the duration of the quasi-experiment, as illustrated in Figures 5.2(b) and 5.3(b), respectively. C1 W and C1 E were used to test the short term effect of plants, and the potential intra-group variance and inter-group variance of the effect of plants

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on thermal comfort. Therefore, one of these rooms contained plants for the first two weeks of each test session, and then the plants were moved to the other room for the final two weeks of each test session. During the intermittent weeks between test sessions, the plants stayed in the room where they were in the final week of the last test session, as described in Table 5.1. This method ensured that each room was evaluated for inter-group and intra-group variance. By keeping the plants in the room during the time periods in between quasi-experiment months, the effect of plants in a room for a longer period of time without the instantaneous addition of the plants at the beginning of each test session was able to be analyzed and compared to the results of the instantaneous addition of plants at the third week of each test session for both rooms, as described in Table 5.1. In addition, this methodology allowed for the evaluation of the short term and long term effect of plants on thermal comfort. Furthermore, the results of both rooms in C1 can be compared to the results of E1 and D1, in order to provide additional inter-group variance analysis. However, it is important to note that the different orientation between the south and north oriented rooms may have had an impact on occupant thermal comfort. Therefore, the test was designed to provide analysis of similar oriented rooms, by evaluating two comparable south facing rooms and two comparable north facing rooms. A more detailed description of the performance of the environmental parameters throughout the quasi-experiment can be found in Section 3.5 and Appendix 5.A.

Week	Setpoint	Winter	Setpoint	Spring	Summer	Fall
1	21.5˚C	BA	22.0˚C	AB	BA	AB
2	21.5˚C	AB	Extreme	AB	BA	AB
3	Extreme	AB	Extreme	BA	AB	BA
4	Extreme	BA	22.0˚C	BA	AB	BA
5	22.0˚C	BA	-----	-----	-----	-----
6	22.0˚C	AB	-----	-----	-----	-----

TABLE 5.1 Plant location in C1 W and C1 E, respectively, throughout the duration of the quasi-experiment

Note: A = Plants present in room, B = No plants present in room

In terms of the presence of vegetation before the beginning of the quasi-experiment, D1, C1 W, and C1 E originally had one tall plant, approximately 2.5 m high, including the planter, as well as two small indoor plants of approximately 40-50 cm height, including the planter, located within each room. E1 originally had three small indoor plants of 40-50 cm height. Multiple participants noted that the existing small plants were not aesthetically pleasing. When the new plants were added, numerous participants remarked that the new plants were more aesthetically pleasing. The original and new plants were provided by the same horticulture company, and they were all grown via a standard hydro culture growth method. The original plants in D1, C1 W and C1 E were removed one month before the beginning of the quasi-experiment, in order to limit a potential negative influence of the removal of the plants on the results of the quasi-experiment. The new plants were added one month before the beginning of the quasi-experiment, in order to limit a potential positive influence of the addition of the plants on the results of the quasi-experiment. During the entire quasi-experiment, E1 had 23 plants and D1 did not contain any plants, as illustrated in Figures 5.2(b) and 5.3(b), respectively. There were 30 plants in C1 at all times, which were moved between C1W and C1E according to the previously described methodology. The plants were installed in such a way that a plant was visible in the foreground and background of every workstation, as illustrated in Figure 5.4 and Figure 5.5(a). Three different sizes of plants were used: tall desk plants of approximately 60-90 cm including the planter, short desk plants of approximately 40-50 cm including the planter, and tall floor plants of approximately 2.5 m including the planter. In addition, tall floor plants were placed near every workstation, in order to give the occupants a sense of vegetation canopy. The species of short desk plants used in this study were *Dracaena surculosa*, *Pleomele* 'Anita', *Anthurium*, *Aglaonema*, *Asparagus*, *Pleomele* 'Song of India', and *Ficus elastic*. The species of tall plants were *Dracaena deremensis, Dracaena marginata, Aralia* 'Fabian', *Howea forsteriana*, and *Rhapis excelsa*. The quantity and arrangement of plants were limited to avoid creating too dense of a vegetated space that would alter the occupants' sense of privacy, the quality of the acoustic environment, and other work environment conditions. These considerations were important in order to minimize the number of environmental conditions that were affected by the presence of the plants in the workspace. This strategy was developed in order to limit the change in the office environments to the presence and non-presence of plants, in order to be able to evaluate the effect of plants on thermal comfort.

§ 5.2.3.7 Quasi-experiment deception dilemma design + evaluation methodology

A key concern throughout the quasi-experiment was ensuring the occupants did not discern the goal of the research project, which has been found to influence the participants' responses.[178] Therefore, the participants were told that the thermal comfort questionnaire was being used to evaluate the performance of the existing climate system, in order to improve their comfort in the future, by developing customized setpoints for each workgroup based on their responses. They were also told the quasi-experiment was part of one of the author's PhD research, which was focused on improving the design of office buildings. In order to justify the presence of the plants, a second questionnaire was given to all participants at the beginning of each test month. This questionnaire included questions about participant creativity, productivity, health, comfort, and well-being. The participants were told the plants were added to evaluate the effect of plants on worker performance, which would be evaluated in this second questionnaire. The researchers asked random participants infrequently throughout the quasi-experiment which workspace factors they believed were affecting their thermal comfort. It is interesting to note that no one reported plants affecting their thermal comfort. This finding suggests that the occupants were not aware of the effect of plants on their reported thermal comfort, or the true goal of the quasi-experiment.

§ 5.3 Results and discussion

§ 5.3.1 Results analysis overview

The quasi-experiment data was initially analyzed descriptively. The participants' responses were grouped by room, and each week was analyzed individually, for every week of the quasi-experiment throughout the four months the quasi-experiment was conducted, as demonstrated in Tables 5.2 and 5.3. The data was separated into individual weeks because the indoor operative temperature of the test rooms were varied per week, as previously described in Section 2.3.5. The analysis of the weekly results from the participants of the individual rooms provides a general understanding of the thermal comfort of the room occupants, as well as the conditions of the rooms at the different temperature profiles and seasons that were evaluated throughout the course of the quasi-experiment. The quasi-

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experiment results were then analyzed using logistic regression analysis, in order to statistically evaluate the effect of plants, and the other measured environmental variables, on occupant thermal comfort. The results of these analyses are presented in the following sections.

§ 5.3.2 Plant effect on thermal comfort analysis

§ 5.3.2.1 Plant effect on thermal comfort descriptive analysis

General effect of plants on participants' thermal comfort

Figures 5.6 and 5.7 indicate that the participants' thermal comfort was greater when plants were present in the room, throughout the operative temperature range that was evaluated, and in regards to every room that was evaluated. For example, it is interesting to note that the participants in D1 more commonly voted being highly thermally uncomfortable, with more votes of '6' '7' '2' and '1', than in E1, even though both rooms experienced comparably similar operative temperature range.

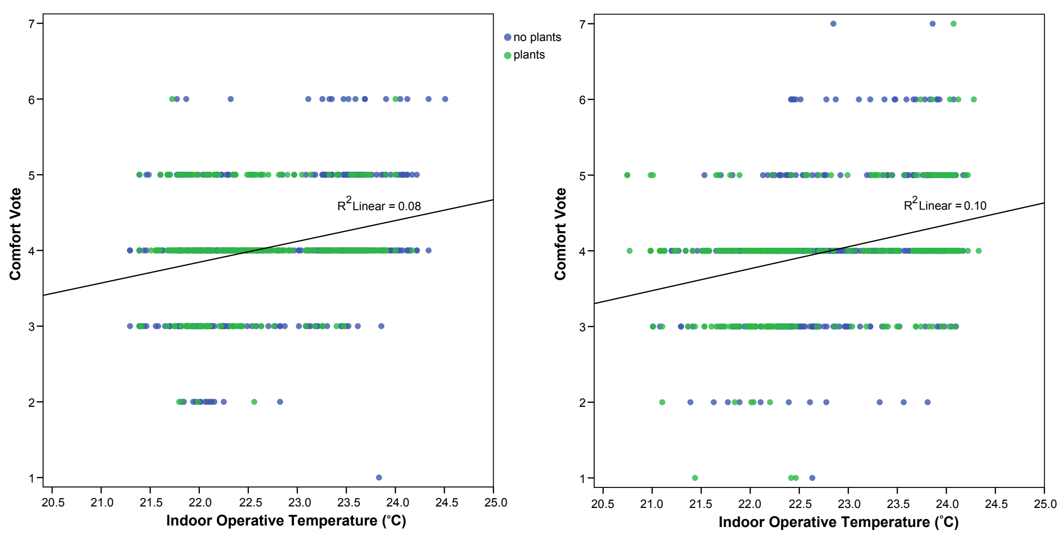

FIGURE 5.6 **(a)** C1 W Scatter of comfort vote and indoor temperature **(b)** C1 E Scatter of comfort vote and indoor temperature

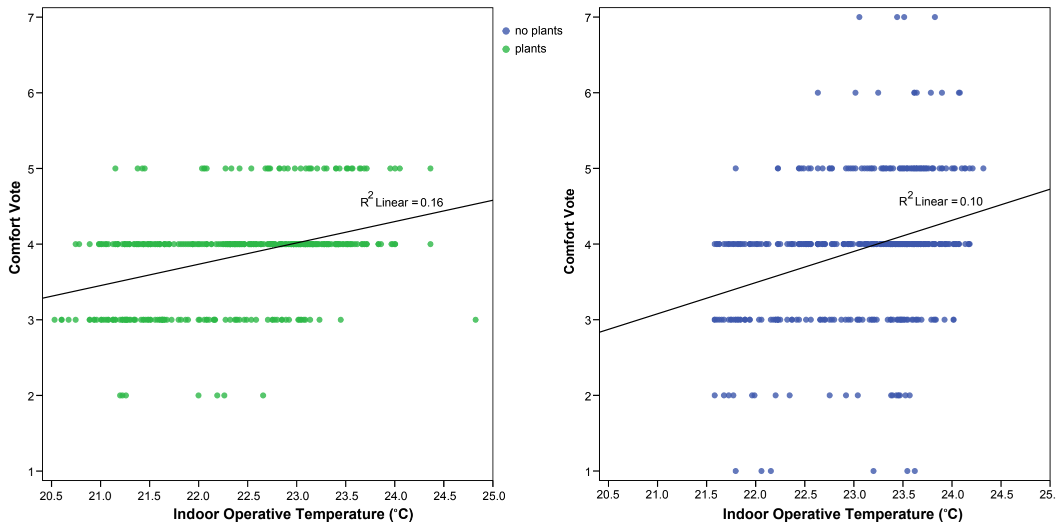

FIGURE 5.7 **(a)** E1 Scatter of comfort vote and indoor temperature **(b)** D1 Scatter of comfort vote and indoor temperature

As illustrated in Table 5.3, the thermal comfort of occupants of E1 and D1 were relatively constant throughout the seasons and various setpoints, with the exception of the initial winter season for E1. These results indicate that the effect of plants on thermal comfort was not reduced over time, or by season. In addition, the thermal comfort of the occupants of E1 was more consistent, and greater, than the thermal comfort of the occupants of D1. The occupants of E1 were on average approximately 8.0% more comfortable than the occupants of D1, in terms of the average thermal comfort of the occupants of each room per week.
In terms of the COMFBOTH thermal comfort model, the occupants of C1 W and C1 E were both on average approximately 12.0% more thermally comfortable when plants were in the room, in terms of the average thermal comfort of the occupants of each room per week. (see Table 5.2) The presence of plants had an effect on occupant thermal comfort in both C1 W and C1 E, both during weeks of typical temperature ranges and more extreme temperature ranges. Furthermore, the thermal comfort of the occupants of C1 W when plants were present in the room was relatively similar to the thermal comfort of the occupants of E1, and the thermal comfort of the occupants of C1 W when plants were not in the room was relatively similar to the thermal comfort of the occupants of D1, as described in Tables 5.2 and 5.3. These results indicate that the presence of plants positively impacted occupant thermal comfort both in the short term and long term, and that the relatively recent addition of plants to a room did not have a substantially higher effect on occupant thermal comfort than the long term presence of plants within a room.

Room: C1W						Room: C1E					
Variable	N	Min.	Max.	Mean	Std. Dev.	Variable	N	Min.	Max.	Mean	Std. Dev.
Winter	Week 1: 21.5°C Setpoint				No Plants	Winter	Week 1: 21.5°C Setpoint				Plants
Indoor operative temp (°C)	114	21.29	22.35	21.81	0.30	Indoor operative temp (°C)	114	20.75	21.92	21.40	0.32
Thermally comfortable*	72	0.00	1.00	0.53		Thermally comfortable*	58	0.00	1.00	0.67	
Winter	Week 2: 21.5°C Setpoint				Plants	Winter	Week 2: 21.5°C Setpoint				No Plants

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Indoor operative temp (°C)	76	21.39	22.71	22.01	0.35	Indoor operative temp (°C)	76	21.01	22.06	21.62	0.31
Thermally comfortable*	49	0.00	1.00	0.53		Thermally comfortable*	32	0.00	1.00	0.59	
Winter	Week 3: 23.0°C Setpoint				Plants	Winter	Week 3: 23.0°C Setpoint				No Plants
Indoor operative temp (°C)	114	22.06	22.80	22.42	0.19	Indoor operative temp (°C)	114	22.11	22.99	22.49	0.19
Thermally comfortable*	61	0.00	1.00	0.77		Thermally comfortable*	57	0.00	1.00	0.68	
Winter	Week 4: 23.0°C Setpoint				No Plants	Winter	Week 4: 23.0°C Setpoint				Plants
Indoor operative temp (°C)	133	22.49	23.62	23.01	0.28	Indoor operative temp (°C)	133	21.72	23.21	22.61	0.35
Thermally comfortable*	84	0.00	1.00	0.71		Thermally comfortable*	46	0.00	1.00	0.83	
Winter	Week 5: 22.0°C Setpoint				No Plants	Winter	Week 5: 22.0°C Setpoint				Plants
Indoor operative temp (°C)	114	21.65	22.85	21.91	0.19	Indoor operative temp (°C)	114	21.53	22.59	22.18	0.29
Thermally comfortable*	65	0.00	1.00	0.60		Thermally comfortable*	33	0.00	1.00	0.76	
Winter	Week 6: 22.0°C Setpoint				Plants	Winter	Week 6: 22.0°C Setpoint				No Plants
Indoor operative temp (°C)	114	21.51	22.39	21.87	0.18	Indoor operative temp (°C)	114	21.65	22.75	22.17	0.28
Thermally comfortable*	49	0.00	1.00	0.69		Thermally comfortable*	48	0.00	1.00	0.65	
Spring	Week 1: 22.0°C Setpoint				Plants	Spring	Week 1: 22.0°C Setpoint				No Plants
Indoor operative temp (°C)	95	21.84	22.66	22.37	0.18	Indoor operative temp (°C)	95	22.23	22.97	22.56	0.21
Thermally comfortable*	45	0.00	1.00	0.91		Thermally comfortable*	37	0.00	1.00	0.57	
Spring	Week 2: 25.0°C Setpoint				Plants	Spring	Week 2: 25.0°C Setpoint				No Plants
Indoor operative temp (°C)	76	23.08	24.00	23.60	0.27	Indoor operative temp (°C)	76	23.35	24.20	23.76	0.26
Thermally comfortable*	30	0.00	1.00	0.83		Thermally comfortable*	45	0.00	1.00	0.60	
Spring	Week 3: 25.0°C Setpoint				No Plants	Spring	Week 3: 25.0°C Setpoint				Plants
Indoor operative temp (°C)	95	23.26	24.34	23.74	0.28	Indoor operative temp (°C)	76	23.40	24.33	23.93	0.19
Thermally comfortable*	31	0.00	1.00	0.74		Thermally comfortable*	68	0.00	1.00	0.78	
Spring	Week 4: 22.0°C Setpoint				No Plants	Spring	Week 4: 22.0°C Setpoint				Plants
Indoor operative temp (°C)	114	21.89	22.82	22.32	0.28	Indoor operative temp (°C)	114	21.56	22.47	22.06	0.18
Thermally comfortable*	49	0.00	1.00	0.76		Thermally comfortable*	54	0.00	1.00	0.80	
Summer	Week 1: 22.0°C Setpoint				No Plants	Summer	Week 1: 22.0°C Setpoint				Plants
Indoor operative temp (°C)	95	21.82	22.49	22.17	0.20	Indoor operative temp (°C)	95	21.99	22.59	22.26	0.13
Thermally comfortable*	28	0.00	1.00	0.68		Thermally comfortable*	32	0.00	1.00	0.81	
Summer	Week 2: 25.0°C Setpoint				No Plants	Summer	Week 2: 25.0°C Setpoint				Plants
Indoor operative temp (°C)	133	23.21	24.51	23.74	0.35	Indoor operative temp (°C)	133	23.16	24.16	23.86	0.23
Thermally comfortable*	43	0.00	1.00	0.74		Thermally comfortable*	44	0.00	1.00	0.82	
Summer	Week 3: 25.0°C Setpoint				Plants	Summer	Week 3: 25.0°C Setpoint				No Plants
Indoor operative temp (°C)	152	23.14	24.17	23.53	0.23	Indoor operative temp (°C)	152	23.50	24.10	23.85	0.13

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Thermally comfortable*	43	0.00	1.00	0.98		Thermally comfortable*	61	0.00	1.00	0.77	
Summer	Week 4: 22.0°C Setpoint				Plants	Summer	Week 4: 22.0°C Setpoint				No Plants
Indoor operative temp (°C)	133	22.52	23.88	22.94	0.36	Indoor operative temp (°C)	133	22.35	23.86	22.93	0.34
Thermally comfortable*	49	0.00	1.00	0.77		Thermally comfortable*	55	0.00	1.00	0.76	
Fall	Week 1: 22.0°C Setpoint				Plants	Fall	Week 1: 22.0°C Setpoint				No Plants
Indoor operative temp (°C)	190	22.67	24.82	23.30	0.38	Indoor operative temp (°C)	95	22.15	23.02	22.39	0.17
Thermally comfortable*	31	0.00	1.00	0.97		Thermally comfortable*	34	0.00	1.00	0.74	
Fall	Week 2: 25.0°C Setpoint				Plants	Fall	Week 2: 25.0°C Setpoint				No Plants
Indoor operative temp (°C)	95	23.18	23.83	23.46	0.20	Indoor operative temp (°C)	95	22.96	24.00	23.41	0.27
Thermally comfortable*	20	0.00	1.00	0.90		Thermally comfortable*	54	0.00	1.00	0.70	
Fall	Week 3: 25.0°C Setpoint				No Plants	Fall	Week 3: 25.0°C Setpoint				Plants
Indoor operative temp (°C)	95	23.11	23.79	23.42	0.19	Indoor operative temp (°C)	95	23.22	23.99	23.47	0.20
Thermally comfortable*	42	0.00	1.00	0.83		Thermally comfortable*	36	0.00	1.00	0.83	
Fall	Week 4: 22.0°C Setpoint				No Plants	Fall	Week 4: 22.0°C Setpoint				Plants
Indoor operative temp (°C)	95	21.96	22.87	22.28	0.19	Indoor operative temp (°C)	95	21.80	22.39	22.11	0.16
Thermally comfortable*	32	0.00	1.00	0.88		Thermally comfortable*	38	0.00	1.00	0.82	

**thermal comfort = COMFBOTH ('3' '4' or '5' thermal sensation vote + '2' thermal preference vote)*

TABLE 5.2 Summary of weekly indoor operative temperature and thermal comfort of C1 W and C1 E

Room: E1	Constant Plants					Room: D1	Constant No Plants				
Variable	N	Min.	Max.	Mean	Std. Dev.	Variable	N	Min.	Max.	Mean	Std. Dev.
Winter	Week 1: 22.0°C Setpoint										
Indoor operative temp (°C)	95	21.08	22.42	21.57	0.42						
Thermally comfortable*	41	0.00	1.00	0.68							
Winter	Week 2-5: 21.5°C Setpoint										
Indoor operative temp (°C)	342	20.90	22.80	21.47	0.38						
Thermally comfortable*	102	0.00	1.00	0.60							
Winter	Week 6: 23.0°C Setpoint										
Indoor operative temp (°C)	114	22.00	23.71	22.65	0.40						
Thermally comfortable*	29	0.00	1.00	0.93							
Spring	Week 1: 22.0°C Setpoint					Spring	Week 1: 22.0°C Setpoint				
Indoor operative temp (°C)	95	21.58	23.26	22.68	0.33	Indoor operative temp (°C)	95	21.75	23.11	22.55	0.38
Thermally comfortable*	41	0.00	1.00	0.88		Thermally comfortable*	48	0.00	1.00	0.79	
Spring	Week 2-3: 25.0°C Setpoint					Spring	Week 2-3: 25.0°C Setpoint				
Indoor operative temp (°C)	171	22.60	24.05	23.23	0.47	Indoor operative temp (°C)	171	23.04	23.81	23.50	0.18

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Thermally comfortable*	52	0.00	1.00	0.87		Thermally comfortable*	63	0.00	1.00	0.78	
Spring	Week 4: 22.0°C Setpoint					Spring	Week 4: 22.0°C Setpoint				
Indoor operative temp *(°C)*	114	21.56	22.97	22.16	0.41	Indoor operative temp *(°C)*	114	21.58	22.35	21.87	0.21
Thermally comfortable*	31	0.00	1.00	0.84		Thermally comfortable*	59	0.00	1.00	0.69	
Summer	Week 1: 22.0°C Setpoint					Summer	Week 1: 22.0°C Setpoint				
Indoor operative temp *(°C)*	95	21.44	22.97	22.42	0.34	Indoor operative temp *(°C)*	95	22.18	23.09	22.54	0.25
Thermally comfortable*	31	0.00	1.00	0.83		Thermally comfortable*	31	0.00	1.00	0.79	
Summer	Week 2-3: 25.0°C Setpoint					Summer	Week 2-3: 25.0°C Setpoint				
Indoor operative temp *(°C)*	285	23.23	24.48	23.72	0.29	Indoor operative temp *(°C)*	285	22.92	24.32	23.62	0.31
Thermally comfortable*	83	0.00	1.00	0.87		Thermally comfortable*	126	0.00	1.00	0.79	
Summer	Week 4: 22.0°C Setpoint					Summer	Week 4: 22.0°C Setpoint				
Indoor operative temp *(°C)*	133	22.39	23.96	23.03	0.37	Indoor operative temp *(°C)*	133	22.32	23.90	23.17	0.44
Thermally comfortable*	33	0.00	1.00	0.85		Thermally comfortable*	41	0.00	1.00	0.83	
Fall	Week 1: 22.0°C Setpoint					Fall	Week 1: 22.0°C Setpoint				
Indoor operative temp *(°C)*	95	22.84	24.00	23.35	0.34	Indoor operative temp *(°C)*	95	23.08	24.07	23.56	0.33
Thermally comfortable*	28	0.00	1.00	0.96		Thermally comfortable*	32	0.00	1.00	0.84	
Fall	Week 2-3: 25.0°C Setpoint					Fall	Week 2-3: 25.0°C Setpoint				
Indoor operative temp *(°C)*	190	22.67	24.82	23.30	0.38	Indoor operative temp *(°C)*	190	22.94	24.07	23.48	0.23
Thermally comfortable*	57	0.00	1.00	0.93		Thermally comfortable*	60	0.00	1.00	0.87	
Fall	Week 4: 22.0°C Setpoint					Fall	Week 4: 22.0°C Setpoint				
Indoor operative temp *(°C)*	76	21.82	23.56	22.57	0.45	Indoor operative temp *(°C)*	76	21.96	23.16	22.60	0.35
Thermally comfortable*	24	0.00	1.00	0.83		Thermally comfortable*	34	0.00	1.00	0.76	

**thermal comfort = COMFBOTH ('3' '4' or '5' thermal sensation vote + '2' thermal preference vote)*

TABLE 5.3 *Summary of weekly indoor operative temperature and thermal comfort of E1 and D1*

Effect of plants on participant thermal comfort during the winter

In general, the occupants of C1 and E1 were less thermally comfortable during the winter colder than typical indoor operative temperature range weeks and typical indoor operative temperature range weeks than at any other time and temperature range the participants experienced during the quasi-experiment. There was a partial exception in regards to the occupants of C1 E.

As shown in Table 5.2, the occupants of C1 W were more thermally uncomfortable during the colder than typical indoor operative temperature winter test periods, both with and without plants, than during the other warmer test periods. The occupants of C1 W were approximately 12.5% more thermally comfortable during these winter weeks when plants were present in the room. It is also interesting to note that although the average indoor operative temperature of the warm winter week in C1 W with plants (Winter Week 2) was 0.58°C colder than the warm winter week of C1 W without plants (Winter Week 3), the occupants of C1 W were approximately 6.0% more thermally comfortable in the presence of plants.

In contrast, the occupants of C1 E were most thermally uncomfortable during the spring typical indoor operative temperature week without plants (Spring Week 1) and the spring warmer than typical indoor operative temperature week without plants (Spring Week 2), as shown in Table 5.2. Besides these two weeks, the winter colder than typical indoor operative temperature range weeks (Winter Weeks 1-2) and typical indoor operative temperature range week without plants (Winter Week 6) were the most thermally uncomfortable weeks for the occupants of C1 E. In contrast, approximately 76.0% of the occupants of C1 E were thermally comfortable during the winter typical setpoint range week with the presence of plants (Winter Week 5). This was higher than the same winter temperature range week without plants (Winter Week 6), approximately 65.0%, and similar to the thermal comfort of the occupants of C1 E during the summer and fall weeks without plants. The occupants of C1 E were also more thermally comfortable during the cold winter weeks when plants were present in the room, by an average of 10.0%.

Therefore, these results indicate that the presence of plants had a substantial positive effect on occupant thermal comfort in the winter, even though the average thermal comfort of the occupants was generally lower during the winter test period than during the test periods of the other warmer seasons. Although thermal comfort research generally evaluates occupant thermal comfort in cooling load conditions, the results of this research indicate it is important to further research the effect of winter outdoor and indoor temperatures on occupant thermal comfort.

Non-winter seasonal effects of plants on participants' thermal comfort

Depending on the season and room, the presence of plants had a greater effect on the participants' thermal comfort at different indoor operative temperature ranges. For example, during the spring and fall test period, occupants of E1 were slightly less comfortable in warmer indoor operative temperatures than at the typical indoor operative temperature range, by approximately 1.0% - 3.0%, as shown in Table 5.3. However, in the summer test period, occupants of E1 were slightly more comfortable in warmer indoor operative temperatures than at the typical indoor operative temperature range, by approximately 2.0 - 4.0%.

In addition, in C1 W during the summer test session, the presence of plants improved occupant thermal comfort by approximately 24.0% when the average indoor operative temperature was 23.74° C (Summer Week 3). In contrast, the presence of plants improved occupant thermal comfort by approximately 9.0% during the summer test week (Summer Week 4) when the average indoor operative temperature was 22.94° C, as described in Table 5.2. In C1 E, on the other hand, the presence of plants during the summer test session improved occupant thermal comfort by approximately 5.0% when the average indoor operative temperate was approximately 23.86° C (Summer Week 2), as well as when the average indoor operative temperature was 22.93° C (Summer Week 1).

Therefore, the effect of plants on occupant thermal comfort did not consistently vary in accordance with changes in the indoor operative temperature during the non-winter test periods. Furthermore, in order to assess the relationship between the presence of plants, occupant thermal comfort, and the various environmental variables in more depth, a logistic regression analysis of the recorded data was conducted.

§ 5.3.3 Thermal comfort definition analysis

It is interesting to note that the COMFFEEL thermal comfort definition resulted in 94.0% of all thermal comfort votes in C1 E being defined as thermally comfortable, 95.0% of thermal comfort votes in C1 W, 98.0% of thermal comfort votes in E1, and 92.0% of thermal comfort votes in D1. In contrast, the COMFBOTH thermal comfort definition resulted in 73.0% of all thermal comfort votes in C1 E being defined as thermally comfortable, 75.0% of thermal comfort votes in C1 W, 81.0% of thermal comfort votes in E1, and 79.0% of thermal comfort votes in D. The COMF(4) thermal comfort definition resulted in 61.0% of all thermal comfort votes in C1 E being defined as thermally comfortable, 60.0% of thermal comfort votes in C1 W, 67.0% of thermal comfort votes in E1, and 55.0% of thermal comfort votes in D1.

Furthermore, a number of participants verbally noted they were thermally uncomfortable to the researchers at various times throughout the quasi-experiment, when the researchers were in the test rooms collecting thermal sensor data. The participants' vocal thermal comfort seemed to be in closer agreement to the results of the logistic regression analysis of the COMFBOTH and COMF (4) thermal comfort models. In addition, besides the R^2 value as defined by Nagelkerke in C1 E, the R^2 value and the model chi square values of the COMFFEEL thermal comfort models for both C1 W and C1 E were less than the R^2 value and model chi square values of the COMFBOTH thermal comfort models for both C1W and C1 E, as shown in Tables 5.4-5.7 and Tables 5.10-5.13, respectively. In C1 E, the R^2 value, according to Nagelkerke, of the COMFBOTH thermal comfort model, was slightly less than the COMFFEEL model, R^2 =.04 and R^2=.06, respectively. These results indicate that COMFFEEL was not as good a fit of the data as COMFBOTH. In addition, for C1 W, the R^2 value, as defined by Cox & Snell, for COMFFEEL (R^2 = .03) was less than for COMF (4) definition (R^2=.07), although the R^2 value, as defined by Nagelkerke, was similar, R^2 =.10 and R^2=.11, respectively. However, the R^2 values and model chi square values of the COMFFEEL thermal comfort model for C1 E were slightly greater than for the COMF (4) model. Nevertheless, when also taking into consideration that the COMFFEEL thermal comfort definition resulted in so few cases being defined as not thermally comfortable, it is apparent that the COMFFEEL thermal comfort model was inaccurate. The inaccuracy of the COMFFEEL thermal comfort model is further demonstrated by the odds ratio and confidence intervals of the clothing insulation predictor in both C1 W and C1 E COMFFEEL thermal comfort models, as shown in Tables 5.6 and 5.12, respectively. Thus, the definition of thermal comfort as a '3' '4' or '5' thermal sensation vote (COMFFEEL) was found in this quasi-experiment to be inadequate to determine occupant thermal comfort.

For both C1 W and C1 E, in terms of the three thermal comfort definitions used in the logistic regression analysis of this quasi-experiment, the thermal comfort models were significantly better at predicting occupant thermal comfort with the environmental variables included, as demonstrated by the model chi square values of the thermal comfort models that are noted in Tables 5.4-5.15. It is important to note that for the COMFBOTH thermal comfort definition, the model chi square value of the thermal comfort models in both C1 W and C1 E was higher, in comparison to the model chi square values of the thermal comfort models that used the other two thermal comfort definitions, COMFFEEL and COMF (4). In C1 E, the COMFBOTH model was also more statistically significant ($p<.01$), than the COMF (4) model ($p=.02$). These results indicate that the COMFBOTH model was better able to predict the participants' thermal comfort than the other two thermal comfort models.

In terms of how well the different thermal comfort definitions and models fit the data, the COMFBOTH thermal comfort models for both C1 W and C1 E were also the best fit for both datasets, as described in Tables 5.4-5.15. Furthermore, the CW COMFBOTH thermal comfort general and parsimonious models (Cox & Snell = .10 and Nagelkerke =.15), were a considerably better fit of the data, and therefore a better predictor of the participants' thermal comfort votes, than the CE general and parsimonious models (Cox & Snell = .02 and Nagelkerke =.03), as shown in Tables 5.4-5.5 and 5.10-5.11, respectively. It is important to note that the R^2 values of the different thermal comfort models presented in Tables 5.4-5.15 should be evaluated cautiously, because the value of R in logistic regression analysis is dependent upon the Wald statistic, which has been found to be inaccurate in certain cases.[316] In addition, the R^2 values of the thermal comfort models are relatively low. Since the models are focused on analyzing human behavior, a relatively low R^2 value is to be expected.

Furthermore, thermal comfort models that analyze datasets with a relatively small range of indoor operative temperatures, as in the case of this dataset, have been found to be inaccurate in predicting future occupant thermal comfort. The addition of a Griffiths constant to thermal comfort models has been found to resolve this problem in some cases.[336] However, since the focus of this quasi-experiment and analysis is on evaluating the effect of the presence of plants on occupant thermal comfort, not on developing a model that predicts the future thermal comfort of the occupants, this further analysis is outside the scope of this chapter.

Regardless of the R^2 value, the measured interrelationships among the predictors are statistically valid.[264] Thus, it is important to consider the statistically significant predictors of the developed thermal comfort models, including the presence of plants.

§ 5.3.4 Plant effect on thermal comfort logistic regression analysis

It is important to note that for both C1 E and C1 W, in regards to all three thermal comfort definitions, plants had a significant, positive effect on the participants' thermal comfort ($p<.01$). Furthermore, in C1 E and C1 W, the presence of plants was the most significant predictor for all three thermal comfort models, both in regards to the overall models and parsimonious models. In some of the models, another predictor was as significant as the presence of plants, such as the outdoor running mean temperature in the C1 E COMFBOTH parsimonious model. These findings indicate that plants were the most significant predictor in the models.

In C1 W, the participants were 1.95 times more likely to be comfortable when the plants were present in the room, according to the COMFBOTH thermal comfort definition, as described in Table 5.5. When thermal comfort was defined as COMFFEEL, the participants were 3.67 times more likely to be comfortable when the plants were in the room. When thermal comfort was defined as COMF (4), the participants were 1.62 times more likely to be comfortable when plants were in the room.

In C1 E, the participants were approximately 1.79 times more likely to be comfortable when the plants were in the room, according to the COMFBOTH thermal comfort definition, as shown in Table 5.11. When thermal comfort was defined as COMFFEEL, the participants were 2.58 times more likely to be comfortable when the plants were in the room. When thermal comfort was defined as COMF (4) , the participants were 1.52 times more likely to be comfortable when plants were in the room.

Model: Thermal Comfort = *3,4, or 5 sens + 2 pref*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.67* (0.19)	0.00	1.35	1.96	2.85
Indoor operative temperature *(°C)*	0.28* (0.14)	0.05	1.00	1.32	1.75
Gender *(female = 1)*	-0.44* (0.22)	0.05	0.42	0.65	0.99
Clothing insulation *(clo)*	1.49* (0.58)	0.01	1.43	4.43	13.67
Metabolic rate *(W/m²)*	0.04* (0.01)	0.00	1.04	1.02	1.06
Relative humidity *(%)*	0.01 (0.01)	0.36	0.99	1.01	1.04
Outdoor running mean temp (α = 0.8) (°C)	0.04 (0.03)	0.16	0.98	1.04	1.10
Constant	-9.91 (3.52)	0.01			

TABLE 5.4 Room C1 W COMFBOTH general logistic regression thermal comfort model

*Note: R2 = .10 (Cox & Snell), .15 (Nagelkerke). Model x2(1) = 85.83, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens + 2 pref*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.67* (0.18)	0.00	1.37	1.95	2.78
Gender *(female = 1)*	-0.45* (0.22)	0.04	0.42	0.64	0.97
Clothing insulation *(clo)*	1.32* (0.57)	0.02	1.23	3.73	11.29
Metabolic rate *(W/m²)*	0.04* (0.01)	0.00	1.02	1.04	1.06
Outdoor running mean temp (α = 0.8) (°C)	0.07* (0.01)	0.00	1.05	1.08	1.10
Constant	-3.23 (0.84)	0.00			

TABLE 5.5 Room C1 W COMFBOTH parsimonious logistic regression thermal comfort model

*Note: R2 = .10 (Cox & Snell), .15 (Nagelkerke). Model x2(1) = 81.95, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	1.38* (0.48)	0.00	1.56	3.96	10.05
Indoor operative temperature *(°C)*	-0.56* (0.28)	0.05	0.33	0.57	0.99
Gender *(female = 1)*	0.48 (0.48)	0.32	0.63	1.61	4.14
Clothing insulation *(clo)*	1.61 (1.15)	0.16	0.52	4.98	47.39
Metabolic rate *(W/m²)*	0.03 (0.02)	0.11	0.99	1.04	1.08
Relative humidity *(%)*	-0.01 (0.03)	0.82	0.94	0.99	1.05
Outdoor running mean temp (α = 0.8) (°C)	0.13* (0.06)	0.03	1.01	1.14	1.28
Constant	11.05 (6.98)	0.11			

TABLE 5.6 Room C1 W COMFFEEL general logistic regression thermal comfort model

*Note: R2 = .04 (Cox & Snell), .13 (Nagelkerke). Model x2(1) = 33.62, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	1.30* (0.46)	0.00	1.49	3.67	9.07
Indoor operative temperature *(°C)*	-0.58* (0.25)	0.02	0.34	0.56	0.92
Outdoor running mean temp (α = 0.8) (°C)	0.11* (0.03)	0.00	1.05	1.11	1.18
Constant	15.23 (5.69)	0.01			

TABLE 5.7 Room C1 W COMFFEEL parsimonious logistic regression thermal comfort model

*Note: R2 = .03 (Cox & Snell), .11 (Nagelkerke). Model x2(1) = 27.46, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *4 sensation*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.41* (0.16)	0.01	1.10	1.50	2.0
Indoor operative temperature *(°C)*	-0.14 (0.13)	0.28	0.68	0.87	1.12
Gender *(female = 1)*	-0.53* (0.21)	0.01	0.40	0.59	0.88
Clothing insulation *(clo)*	0.48 (0.51)	0.35	0.60	1.61	4.34
Metabolic rate *(W/m^2)*	0.01 (0.01)	0.47	0.99	1.01	1.02
Relative humidity *(%)*	0.01 (0.01)	0.25	0.99	1.01	1.04
Outdoor running mean temp (α = 0.8) (°C)	0.05* (0.02)	0.04	1.00	1.05	1.10
Constant	1.87 (3.04)	0.54			

TABLE 5.8 Room C1 W COMF (4) general logistic regression thermal comfort model

*Note: R2 = .08 (Cox & Snell), .11 (Nagelkerke). Model x2(1) = 65.02, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *4 sensation*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.48* (0.15)	0.00	1.20	1.62	2.19
Gender *(female = 1)*	-0.52* (0.20)	0.01	0.40	0.59	0.88
Outdoor running mean temp (α = 0.8) (°C)	0.06* (0.01)	0.00	1.04	1.06	1.08
Constant	-0.13 (0.13)	0.32			

TABLE 5.9 Room C1 W COMF (4) parsimonious logistic regression thermal comfort model

*Note: R2 = .07 (Cox & Snell), .10 (Nagelkerke). Model x2(1) = 59.96, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens + 2 pref*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.59* (0.17)	0.00	1.31	1.80	2.50
Indoor operative temperature *(°C)*	0.04 (0.13)	0.78	0.80	1.04	1.35
Gender *(female = 1)*	0.29 (0.16)	0.08	0.97	1.34	1.84
Clothing insulation *(clo)*	0.80 (0.63)	0.21	0.64	2.22	7.68
Metabolic rate *(W/m^2)*	0.01 (0.01)	0.30	0.99	1.01	1.03
Relative humidity *(%)*	-0.00 (0.013)	0.96	0.98	1.00	1.03
Outdoor running mean temp (α = 0.8) (°C)	0.04 (0.03)	0.13	0.99	1.04	1.10
Constant	-1.93 (3.33)	0.56			

TABLE 5.10 Room C1 E COMFBOTH general logistic regression thermal comfort model

*Note: R2 = .03 (Cox & Snell), .04 (Nagelkerke). Model x2(1) = 24.95, p< .01 ,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens + 2 pref*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.58* (0.16)	0.00	1.30	1.79	2.50
Outdoor running mean temp (α = 0.8) (°C)	0.03* (0.01)	0.00	1.01	1.03	1.05
Constant	0.46 (0.15)	0.00			

TABLE 5.11 Room C1 E COMFBOTH parsimonious model

*Note: R2 = .02 (Cox & Snell), .03 (Nagelkerke). Model x2(1) = 19.26, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	1.01* (0.33)	0.00	1.43	2.74	5.24
Indoor operative temperature *(°C)*	-0.26* (0.26)	0.31	0.47	0.77	1.27
Gender *(female = 1)*	0.70* (0.31)	0.03	1.09	2.01	3.70
Clothing insulation *(clo)*	1.80* (1.32)	0.17	0.45	6.04	80.23
Metabolic rate *(W/m^2)*	0.00* (0.02)	0.88	0.97	1.00	1.04
Relative humidity *(%)*	0.01* (0.02)	0.57	0.97	1.01	1.06
Outdoor running mean temp (α = 0.8) (°C)	0.02* (0.05)	0.64	0.93	1.02	1.13
Constant	5.81 (6.47)	0.37			

TABLE 5.12 Room C1 E COMFFEEL general logistic regression thermal comfort model

*Note: R2 = .02 (Cox & Snell), .06 (Nagelkerke). Model x2(1) = 19.53, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *3,4, or 5 sens*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.95* (0.33)	0.00	1.36	2.58	4.89
Indoor operative temperature *(°C)*	-0.18 (0.19)	0.33	0.58	0.84	1.20
Gender *(female = 1)*	0.66* (0.31)	0.03	1.06	1.93	3.50
Constant	6.21 (4.28)	0.15			

TABLE 5.13 Room C1 E COMFFEEL parsimonious logistic regression thermal comfort model

*Note: R2 = .02 (Cox & Snell), .05 (Nagelkerke). Model x2(1) = 15.82, p< .01,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *4 sensation*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.36* (0.15)	0.01	1.08	1.43	1.91
Indoor operative temperature *(°C)*	-0.23* (0.12)	0.05	0.63	0.79	1.00
Gender *(female = 1)*	-0.11 (0.15)	0.47	0.67	0.90	1.20
Clothing insulation *(clo)*	0.75 (0.57)	0.18	0.70	2.12	6.42
Metabolic rate *(W/m^2)*	-0.00 (0.01)	0.75	0.98	1.00	1.02
Relative humidity *(%)*	-0.02 (0.01)	0.07	0.96	0.98	1.00
Outdoor running mean temp (α = 0.8) (°C)	0.07* (0.03)	0.01	1.02	1.07	1.12
Constant	5.58 (2.93)	0.06			

TABLE 5.14 Room C1 E COMF (4) general logistic regression thermal comfort model

*Note: R2 = .02 (Cox & Snell), .03 (Nagelkerke). Model x2(1) = 16.78, p =.02,*p<.05, **95% CI for Odds Ratio*

Model: Thermal Comfort = *4 sensation*	B (SE)	Sig.	Lower**	Odds Ratio**	Upper**
Plants *(plants = 1)*	0.42* (0.14)	0.00	1.15	1.52	2.02
Outdoor running mean temp (α = 0.8) (°C)	0.01 (0.01)	0.32	0.99	1.01	1.03
Constant	0.15 (0.14)	0.29			

TABLE 5.15 Room C1 E COMF (4) parsimonious logistic regression thermal comfort model

*Note: R2 = .01 (Cox & Snell), .01 (Nagelkerke). Model x2(1) = 8.88, p =.01,*p<.05, **95% CI for Odds Ratio*

§ 5.3.5 Environment variables analysis

§ 5.3.5.1 Overview of environmental variables analysis

A detailed review of the analyses conducted on the state of the various environmental variables throughout the quasi-experiment is outside the scope of this chapter. A brief overview of the results are provided in the following Sections, as well as in Appendix 5.A. Appendices 5.B-5.E provide a weekly summary of the environmental variables and thermal comfort of the participants of each room.

The state of a number of environmental variables was evaluated through a diverse range of methods and scales. For instance, the range of indoor operative temperatures that occurred within each test room, per season, are described in Figures 5.8 and 5.9, as well as at the scale of the individual week in Tables 5.2 and 5.3. It is important to note that the indoor operative temperature range in C1 E and C1 W varied slightly between different test weeks that were intended to test the same temperature range, due to internal heat gains and solar gain, among other factors, similar to the discussion in Section 2.3.5.

Nonetheless, the influence of naturally occurring variations among the various environmental factors, including indoor operative temperature, was minimized by the design of the quasi-experiment, which was designed to evaluate both inter- and intra-group variance. This was achieved through the evaluation of multiple rooms at the same time, both with and without plants, as well as conducting measurements during multiple seasons. For example, during the Spring test period, the average indoor operative temperature of C1 E during the 22°C setpoint test period without plants was slightly higher than during the 22°C setpoint test period with plants, by approximately 0.5°C, as illustrated in Figure 5.8(b) and Table 5.2. In contrast, the average indoor operative temperature of C1 W during the same test periods were approximately 0.19°C – 0.26°C cooler, respectively, than in C1 E, as shown in Figure 5.8(a) and Table 5.2. Furthermore, the average indoor operative temperature of C1 W was relatively similar for the Spring test periods with and without plants at the 22°C setpoint, with a difference of 0.05°C. In addition, the difference in the average indoor operative temperature of C1 E in the fall test period at the 22°C setpoint, with and without plants, was 0.28°C, approximately half the difference between the spring measurement periods. Thus, these sample data sets, among others, provide a range of comparison metrics and opportunities.

Furthermore, as discussed in Section 2.3.4, the environmental variables that were identified in existing literature as the most influential of thermal comfort were included in the logistic regression analysis of the thermal comfort of the occupants of each room. Thus, the logistic regression analysis evaluated the influence of key environmental variables on occupant thermal comfort, and controlled for the variance of the various environmental factors.

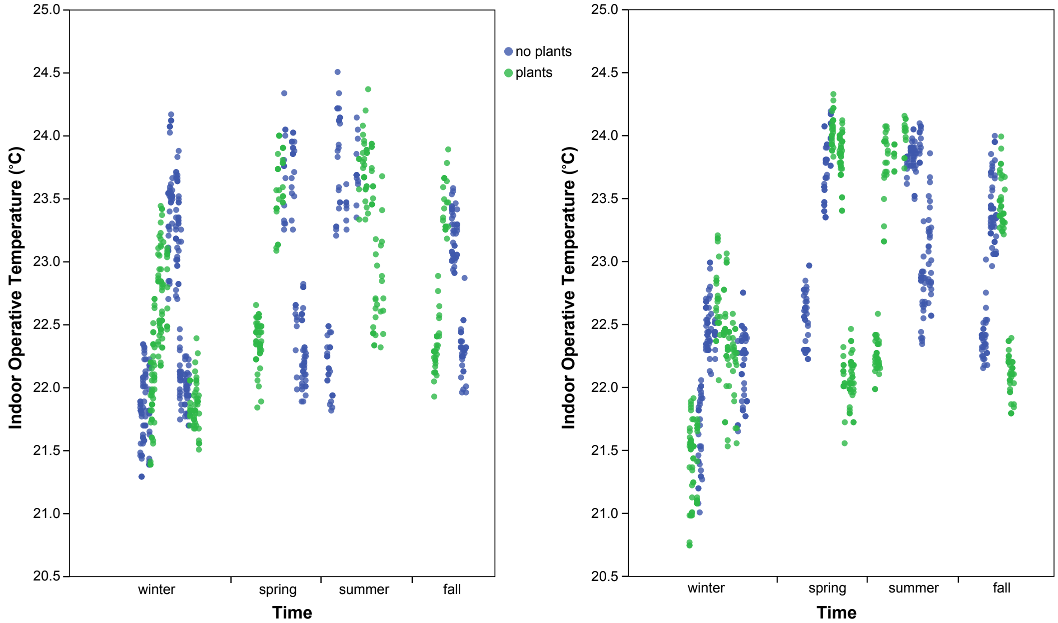

FIGURE 5.8 **(a)** C1 W Indoor operative temperature during quasi-experiment **(b)** C1 E Indoor operative temperature during quasi-experiment

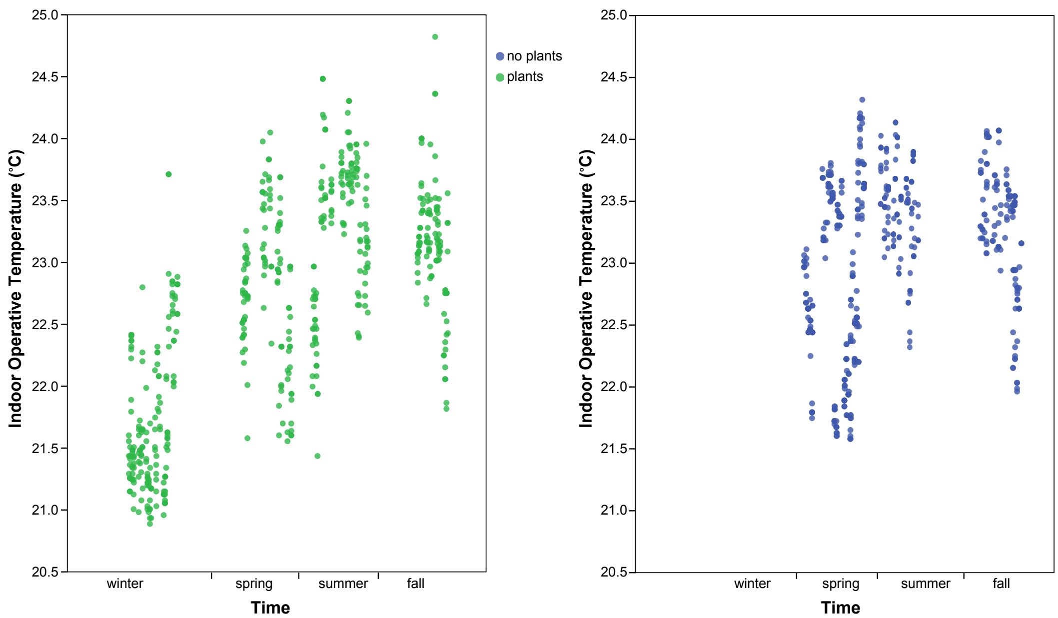

FIGURE 5.9 **(a)** E1 Indoor operative temperature throughout quasi-experiment **(b)** D1 Indoor operative temperature throughout quasi-experiment

§ 5.3.5.2 Influence of vegetation physiological functions on occupant thermal comfort

The presence of the plants, throughout the quasi-experiment, were not found to have a substantial effect on the temperature or humidity of the test rooms. In regards to the influence of physical parameters of work environments on occupant thermal comfort, existing research indicates that occupant thermal comfort is influenced primarily by the temperature of the workspaces. The humidity of test rooms has not been found to substantially impact occupant thermal comfort, with the exception of some cases of considerably hot and humid workspaces.[336] Nevertheless, it is important to note that the relative humidity in C1 W and C1 E, as well as E1 and D1, were relatively similar throughout the test sessions, regardless of the presence of plants, as shown in Appendices 5.B-5.E. This finding indicates that the evapotranspiration processes of the plants did not substantially increase the moisture content of the rooms. Orwell (2006) found similar results.[347]

Based on the measurement of light levels within the test spaces, the plants did seem to influence the light levels within the rooms, as shown in Appendices 5.B-5.E. However, this influence may have been partly due to the location of the plants in relation to the light sensors, as illustrated in Figures 5.2-5.4. In addition, Huang (2012) found that office worker's satisfaction with a room's light level increased as the room's illumination intensity increased, up to approximately 1424 lux.[211] This finding indicates that the effect of plants on the room light levels would negatively affect their visual comfort. However, several experiments have found that occupants with plants in their workspace perceive lower light levels as bright as rooms without plants and higher light levels, which may be a contributing factor to the relatively consistent lower light levels in the test rooms when plants were present.[204, 327, 429] Moreover, light levels have been found to be insignificant in terms of their effect on the general comfort of office workers.[211, 214] Regardless, as previously discussed in Section 2.3.4, it is important to note that the influence of interior light levels on occupant thermal comfort was not included in the final logistic regression analysis because the illumination intensity of the test rooms was found to have a considerably insignificant effect on occupant thermal comfort, both in this study and in existing literature.[142, 336] Furthermore, as discussed in Section 2.3.2, the air velocity speeds within the test rooms were not large enough to impact occupant thermal comfort, and therefore, the effect of plants on the air movement within the rooms was not significant.

These results indicate that the effect of plants on the participants' thermal comfort was primarily psychological, rather than physiological.

§ 5.3.6 Research limitations and future research

Although the results of the presented quasi-experiment were found to be statistically significant, and a relatively large quantity of thermal comfort votes were collected, additional research that evaluates the effect of plants on occupant thermal comfort for a substantially larger sample population, as well as among different cultures, would provide results that could be generalized to a larger population. It is important to note that this would require a substantially larger dedication of financial and human resources. Nevertheless, the results of this quasi-experiment provide support for the value of conducting this type of research in the future.

Due to unexpectedly high internal heat gains during the winter test session, the participants' thermal comfort at lower than normal indoor operative temperatures was not able to be evaluated as in depth or as extensively as the thermal comfort of occupants at higher temperature ranges. The presented results indicate that occupant thermal comfort at these low temperatures is different than at other temperatures, and yet there is currently a lack of existing research on the thermal comfort of occupants in low indoor operative temperature environments. This may partially be because researchers believe occupants have less opportunity to control the temperature of the indoor environment at low temperatures, and therefore are wary to devote resources to evaluate occupant thermal comfort when office buildings are in heating mode. However, a few existing studies have found that occupant thermal comfort in low temperatures can vary substantially, depending on the qualities and opportunities for personal control within the work environment. For example, Luo et al. (2014) found occupants with personal control over their thermal environment had a 2.6 °C lower neutral temperature in a quasi-experiment that evaluated occupant thermal comfort in China during the winter. In addition, occupants with personal control over their environment were found to accept operative temperatures of as low as 15 °C, while occupants of buildings with less opportunities for personal control accepted operative temperatures of 17 °C and higher as comfortable.[282] The results of this chapter indicate that thermal comfort can be improved through design at these low temperatures.

Furthermore, existing research on the effect of plants on the performance and well-being of people within office environments tend to evaluate the effect of a relatively low quantity of plants on the participants. As the results of this chapter demonstrate, the addition of a large quantity of plants to work environments can provide substantial benefits to the occupants. Thus, further research should investigate the potential variable influence of a range of different quantities of plants, and types of occupant interactions with plants, on worker performance and well-being.

§ 5.4 Chapter Conclusion

The presence of a substantial quantity of plants in the work environment was found to have a significant effect on the thermal comfort of the participants in this quasi-experiment, throughout all four seasons, in both typical and more extreme indoor operative temperature ranges, regardless of gender, and according to a number of definitions of occupant thermal comfort. The quasi-experiment was designed in a manner that allowed the effect of the presence of plants to be evaluated both in terms of short term and long term effects, as well as taking into account inter- and intra- group variance. When thermal comfort was defined as a thermal comfort vote of 'slightly cool' (3), 'neutral' (4), or 'slightly warm' (5), and a 'no temperature change' thermal preference vote, occupants of the two rooms where plants were present for half of the quasi-experiment, C1 W and C1 E, were both on average approximately 12.0% more thermally comfortable. Occupants of the room with plants present throughout the quasi-experiment, E1, were on average approximately 8.0% more thermally comfortable than occupants of the room without any plants present throughout the quasi-experiment, D1. Moreover, occupants of C1 E were approximately 1.79 times more likely to be thermally comfortable when plants were present in the room, while occupants of C1 W were 1.95 times more likely to be thermally comfortable when plants were present in the room. Although the occupants of the test rooms were generally less thermally comfortable in the winter during typical and less than typical indoor operative temperature ranges, the presence of plants was found to have a positive effect on occupant thermal comfort in these thermal conditions.

These results indicate that the presence of a substantial quantity of plants within office environments improves occupant thermal comfort, both at typical and more extreme indoor operative temperatures. This effect, in turn, can result in the reduction of the rate of building energy consumption and carbon emission rates, by allowing the temperature set point in offices to be raised in the summer and lowered in winter, while maintaining, or even in some cases improving, occupant thermal comfort. Furthermore, the results of this quasi-experiment indicate that the effect of plants on occupant thermal comfort was psychological in origin, and thereby supports previous research findings that occupant thermal comfort is influenced by both physiological and psychological factors. This finding suggests that the psychological effects and perception of physical environments by building occupants have a direct effect on their thermal comfort and, potentially, the energy consumption of buildings.

The incorporation of plants into work environments have been found to provide a range of additional benefits to building occupants, such as improving worker performance and well-being, including productivity, creativity, stress levels, and air quality satisfaction.[23, 47, 254, 278, 300, 403, 423] Furthermore, occupant productivity has been found to increase when their thermal comfort is improved.[255, 261, 387] Moreover, plants can be effective strategies for improving building performance parameters, such as building energy consumption rates. For example, the incorporation of spatial vegetated environments into outdoor and semi-outdoor work environments has been found to improve the building's energy consumption rates and carbon emissions, by providing physical shading and insulation, as well as reducing the cooling load of the building by temporarily shifting body heat gain loads from the actively conditioned building environment to a passively conditioned work environment.[292] The results of this quasi-experiment indicate that plants can further reduce building energy use and carbon emissions when they are incorporated into these types of environments, by extending the quantity of operating hours occupants perceive these spaces as thermally comfortable, thereby increasing the quantity of body heat gain loads that are shifted to outside the actively conditioned built environment.

Therefore, these findings suggest that the quality of workspaces can reduce the operating energy consumption rates of buildings. Moreover, these findings suggest that the integration of the design of constructed spaces into the design and development of building climate systems, through the collaboration of mechanical engineers and architects, can generate more effective building climate systems and design solutions. Thus, improving occupant thermal comfort through the installation of plants may have far reaching and cost significant positive effects on the performance of buildings and their occupants.

§ 5.5 Acknowledgements

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Worker Performance Section

Introduction

Building and worker performance are inherently interrelated, as discussed and explored in Chapters 3-5. Moreover, the psychological benefits of vegetation substantially outweigh the physiological benefits at the scale of the individual building space, in terms of building energy consumption rates, as well as building operating costs, as shown in Chapter 4.[292] To the extent of the author's knowledge, this conclusion has not been found in existing literature. It is important to note that in order to develop this finding, it was necessary to investigate and compare the potential benefits of both psychological and physiological performance based microforest design. Thus, the results of this research project suggest that, due to the inherent interrelatedness of microforest building and worker performance parameters, it is important to consider both worker and building performance parameters when investigating how to design microforests that are high performing, in terms of building performance or worker performance. Moreover, the findings from this research project indicate that design solutions which effectively address both worker and building performance parameters can generate higher performing design solutions, both in terms of worker and building performance.

This finding played a pivotal role in the direction and focus of this PhD research project, and led to an in-depth investigation of the potential of microforests to improve the work performance of knowledge workers. The results of this investigation are presented in the following two chapters. In order to determine the performance potential of microforests, it was first important to identify and evaluate the potential of the design of workspace environments to improve worker performance. To this end, Chapter 6 presents the results of a systemic literature review of existing findings on the potential of the design of physical environments to improve worker performance, as well as important design issues that should be taken into consideration when developing and evaluating the performance of workspaces. After evaluating the general performance potential of the design of work environments, which thereby generated a clear understanding of the potential influence of the design of work environments on worker performance, the potential worker performance benefits of developing microforests were investigated. Subsequently, the study presented in Chapter 7 further investigated the potential worker performance benefits that can be developed through the design of workspaces. This study investigated the effects of various typical and innovative workspace types, such as microforests, on the performance of knowledge workers, in regards to a range of work tasks.

These investigations resulted in the identification of effective worker performance design strategies, design guidelines, as well as high performance workspace types. Specifically, various types of microforests were found to be preferred substantially more than workspace environments for a diverse range of work tasks. The results of this section indicate that microforests can improve worker performance in diverse ways, depending on their design.

6 Constructing Worker Performance

Identifying and exploring potential design issues, workspace types, and spatial qualities that can improve knowledge worker performance

§ 6.1 Introduction

§ 6.1.1 Investigating the value of defining knowledge worker performance in terms of productivity versus creativity

Historically, business organizations have focused on maximizing productivity to measure the success, effectiveness and value of their company and employees. By focusing on maximizing their output at minimum cost, worker performance has been typically evaluated through measures of productivity, both directly, such as the quantitative output of an employee in a given amount of time, as well as through evaluations of certain personality traits and abilities that research indicates leads to productivity, such as core self-evaluations (CSE).[128, 226, 387] However, the global economy is increasingly shifting from a productivity based economy to an innovation, or knowledge, based economy.[6, 128, 149]

To this end, the development of innovations, and the introduction of these new processes and commercially tradable products into functioning production, marketing, and management systems, are increasingly becoming important metrics for the performance of individual workers and organizations.[15] For instance, business organizations are increasingly measuring the performance and value of their company and employees by their ability to produce innovative products and processes.[128, 149, 401] Moreover, extant research indicates that the most successful individuals, business organizations, and national economies are those that are focused, and most successful, at generating innovative commercial products and processes.[6, 149]

Thus, in terms of evaluating the creative performance of organizations and individuals, it is important to identify and evaluate important factors that influence the innovation development process.
To this end, it is important to consider that the development process of innovations usually requires collaborative efforts between an array of knowledge workers, and is typically divided into two stages: an invention and exploitation stage.[136, 279, 318] The invention stage relies on the creativity of knowledge workers, and involves creative processes such as idea generation and evaluation, as well as the identification of potential opportunities for innovation.[279, 318]

Knowledge workers are the core creative workers of innovation based organizations, and are responsible for creating, distributing, analyzing, and applying theoretical and analytical knowledge to generate innovative products and processes.[114, 129, 149] Knowledge workers provide services such as product development and consultancy work, and include creative professionals in a diverse array of fields, including science, engineering, architecture, design, business, finance, and law.[114, 149] The exploitation stage, on the other hand, is focused on the commercial development and marketing of the invention, and requires a different set of skills, personality traits, organizational structures, and leadership styles.[38, 43] Accounting, marketing, and managerial departments, among others, typically are responsible for successfully implementing inventions. Indeed, it is not uncommon for innovations to be developed by organziations that did not generate the inventions themselves.[43]

Nevertheless, the innovative success of nations is currently being measured by the EU and other nation scale organizations, based on the abilities of nations to attract, retain, and develop creative individuals, as well as to successfully generate innovations from them.[149] This is partly because the ability of knowledge workers to generate innovative products and processes has been found to typically be one of the key factors that determine the success of innovative organizations, despite the lack of involvement of knowledge workers in the exploitation stage of innovation development.[128, 401] In other words, the development of innovations by an organization tends to be dependent on the creativity of the individuals within the organization.

Thus, traditional quantitative productivity measurements are becoming less applicable to innovation driven businesses organizations and nations. These measures of an individual's efficiency in conducting a specific task are giving way to measurements of the effectiveness, or potential, of individual employees to contribute to the success of the organization, such as measurements of employee creativity at the individual scale, as well as organization scale measurements of innovation development.[78, 136, 318] This transition inherently encourages organizations to explore innovative ways to maximize the potential and creativity of their employees.

§ 6.1.2 Identifying the potential influences of physical work environments on knowledge worker creativity

To this end, the influencing factors of work environments on the creative performance of knowledge workers are traditionally organized into three general categories: employee personality, the social-organizational work environment, and the physical work environment.[129, 424] Moreover, it is important to note that existing literature has identified and investigated other influencing factors on worker creativity and performance, such as the pressure of forces outside the workplace, including stress from a knowledge worker's personal life and market pressures.[136] However, since the focus of this chapter is on the potential of the physical work environment to improve knowledge worker performance, a more extensive evaluation of additional influencing factors is outside the scope of this chapter.

Hierarchical scales of influence among these three factors have been proposed in existing literature. For example, based on the results of a survey of 274 knowledge workers that investigated the relative influence of personality, social-organizational factors, and physical work environments on the creativity of knowledge workers, Dul (2011) found evidence that creative personality factors are the most influential on the creative performance of knowledge workers, while physical work environments are the least influential.[129] However, Dul (2011) reported that the difference in contribution of the three factors was small. Moreover, since the conclusions drawn in Dul (2011) were dependent on a survey that did not comprehensively evaluate all the potential influences of the physical environment, or the influences of factors within the other two performance categories, the survey did not provide an adequate evaluation of the relative influence of these three performance categories. In addition, Dul (2011) noted that the authors were unable to determine the relative influence of the various spatial qualities that were evaluated in the survey, and thus the conclusions were based on the assumption that all influencing factors had an equal influence on worker creativity. However, it is probable that the various factors evaluated had different levels of influence, and that some factors that were not evaluated may have an outsize influence on worker performance.

Indeed, numerous research projects have identified a variety of other physical environment factors that influence worker creativity. For example, Forster (2009) found that certain physical workspace types can prime occupants to be creative.[155] Moreover, there is substantial evidence that physical work environments have diverse effects on the performance of building occupants, as discussed in the following subsections and sections of this chapter.

§ 6.1.2.1 Designing workspaces for creative and non-creative work tasks

Existing research on the potential of physical workspaces to affect the creative performance of knowledge workers is largely focused on improving their cognitive ability to generate ideas.[129, 155, 318, 424] However, the development of creative ideas does not occur from sudden bursts of insight. Rather, they are typically developed deliberately over time through a creative process that includes numerous work tasks and cognitive processes that require various skillsets and psychological, as well as environmental, resources.[110, 164]

To this end, several creative phase models have been proposed by various researchers.[110, 164, 279, 439] These existing creative phase models are discussed in more detail in Section 6.2.3. It is important to note that these models identify key work tasks that are conducted during individual and organization scale creative work processes. Furthermore, extant research indicates that workers undergoing creative and non-creative work processes conduct the same work tasks, with the possible exception that non-creative work processes may not involve all of the work tasks that are involved in creative work processes.[279, 318] For instance, there is evidence that some creative work tasks, such as incubation, may not be conducted in non-creative work processes. In addition, the duration of time spent, and relative value, of differrent work tasks, as well as the sequence they are conducted in, may vary between creative and non-creative work processes.[42] Lubart (2001) provides an in-depth review and discussion of these issues.[279] Thus, an evaluation of the effects of physical workspaces on the performance of knowledge workers to conduct individual creative work tasks may also provide an effective evaluation of how these workspaces affect the performance of workers conducting non-creative work tasks. Indeed, improving the creativity of knowledge workers has also been found to improve their overall work performance.[422, 424] For instance, work break activities, or incubating processes, have been found to improve both worker creativity and productivity. For example, exercise has been found to improve worker creativity, productivity, overall work performance, as well as health and well-being.[50, 408, 440] These findings suggest that some work tasks are conducted, and beneficial, for both creative and non-creative work processes.

§ 6.1.2.2 Designing workspaces for individual and group creativity

In addition, although existing literature on worker creativity tends to focus on the creativity of individuals, it is important to consider that inventions are often the result of at least partly collaborative work. For instance, several studies have found that improving individual creativity does not necessitate the production of more innovations or increase the success of business organizations.[440] However, the links between group creativity and individual creativity are not yet well understood, and there is scant existing research that evaluates the factors that promote team creativity.[401, 440] Thus, when designing office environments, it is important for design solutions to develop effective spaces and combinations of spaces that facilitate various work processes for individuals, as well as groups, as discussed in Section 6.4. Moreover, in order to design high performing workspaces, it is important to identify and evaluate the effect of various solutions on individuals, as well as groups.

Unfortunately, existing research has not yet comprehensively evaluated the potential of physical office environments to affect the full range of work tasks and cognitive processes that are engaged by knowledge workers, and which are necessary to generate innovative ideas and products.[401] Thus, further research into the potential effects of physical workspaces on the performance of knowledge workers conducting various creative and non-creative work tasks, at the individual and group scale, is necessary to determine the potential of workspaces to promote the creative and general work performance of knowledge workers and organizations.

§ 6.1.3 Chapter outline

To this end, a review of the existing literature that has investigated how to improve, and in some cases, maximize, the performance of knowledge workers on various work tasks, including the design of physical workspaces, provides the opportunity to determine how to improve the general work performance, and creativity, of individuals and groups. Therefore, the focus of this chapter is on identifying and evaluating workspace types and spatial qualities that will most effectively promote knowledge worker performance on a range of creative and non-creative work tasks. Specifically, a review of existing literature findings on several aspects of physical work environments that have a high potential to impact worker performance for various work tasks, both at the scale of the individual workspace type and the comprehensive office environment, are identified and discussed. This chapter also includes a discussion of the potential performance benefits of innovative workspace types, such as microforests, as well as discussions on numerous factors that may have a considerable influence on the effect of physical workspace types on the performance of knowledge workers on various work tasks. A general outline of the contents of this chapter is illustrated in Figure 6.1.

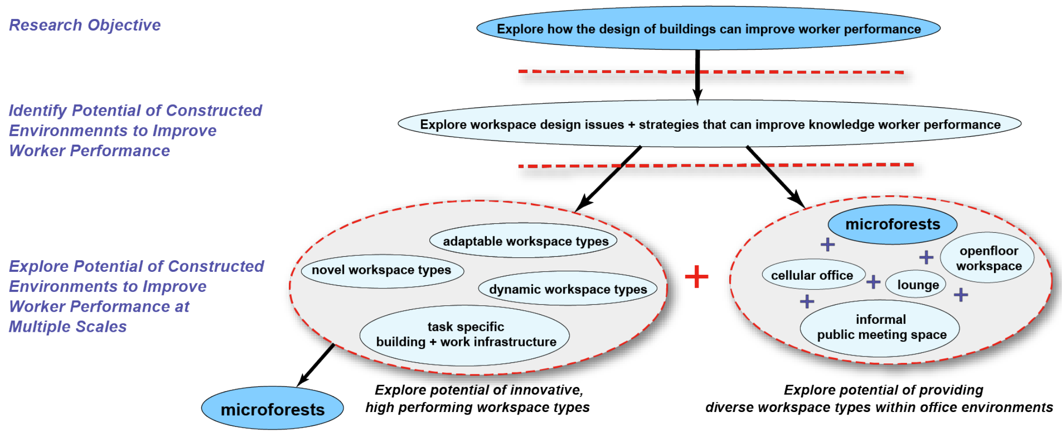

FIGURE 6.1 Constructing worker performance chapter overview

§ 6.2 Exploring workspace design issues + strategies that can improve knowledge worker performance

§ 6.2.1 Creative personality traits

Psychologists have identified a range of key personality traits that are common among highly creative individuals. As discussed in Section 6.1.2, Dul (2011) found evidence that creative personality traits have a greater impact on an individual's creative performance than physical work environments.[129] In addition, Dul (2011) found that the greater a knowledge worker's creative personality, the greater their creative performance.[129] However, as previously discussed, these propositions are not yet conclusive. For instance, the creative process involves a range of tasks, which rely on a broad range of personal skills and resources.[318] In addition, the effects of a wide array of influential factors on an individual's creative performance, including aspects of the physical environments that they interact with, their social-organizational work environment, their creative personality, as well as other external influential factors, such as their personal life, have yet to be evaluated.

Regardless, there is substantial evidence that physical environments influence the personalities of their occupants. For instance, many creative personality traits of highly creative individuals are learned through an individual's interactions with various physical environments.[318] In addition, physical stimuli and environments that improve creative performance have been found to have a greater effect on highly creative people than less creative people.[318] This is partly because creative people tend to have a heightened perceptual awareness, and are therefore more sensitive to environmental stimuli than less creative people.[318] Furthermore, Meusburger (2009) reviewed existing research on the personality traits of creative individuals, and found, among other traits, that they tend to be highly sensitive to aesthetics, attracted to complexity, have a rich and vivid fantasy life, and have a predisposed disposition to integrating diverse stimuli.[318] These personality traits indicate that creative individuals are sensitive to, and may benefit from, physical environments that complement and support these traits, such as forests, and may help explain why these types of physical environments have been found to increase creative performance.[228, 339, 403, 440]

Moreover, existing research suggests that one's perceptual awareness of physical environments can benefit their work performance. For instance, individuals that have acute attention and are sensitive to their surroundings have been found to be able to perceive new trends, as well as upcoming problems and research questions, earlier than others. In addition, early problem finding and problem solving tasks depend on an individual's perceptual discernment and environmental sensitivity.[12]

However, these findings do not necessarily mean that the inhabitation of workspaces that are designed to stimulate creativity will not promote creativity in individuals that are not innately creative. Moreover, the inhabitation of workspaces that promote creativity may improve the creative performance of non-creative occupants. For instance, existing literature indicates that repeated personal interactions with stimulating environments can enhance creative personality traits, such as improving the perceptual awareness of occupants, and in turn, improve an individual's creativity and work performance.[318] Therefore, physical workspaces can be designed to support and enhance the creative personality traits of occupants, in order to improve their creative performance. The design of stimulating workspace types is discussed in more detail in Section 6.3.

Nevertheless, further research is necessary to determine the extent to which the design of physical environments can support and enhance the creative personality traits of individuals. For example, future investigations are needed to determine the effects of different types of physical environments on the creative personality traits of individuals, as well as the effects of various workspace types on different individuals.

§ 6.2.2 Influence of job type, profession, gender, and work experience on creativity

Workspace use rates, the proportion of work time spent on different work tasks, and the effects of physical workspaces on worker performance, vary based on an individual's job type. For instance, managers tend to spend relatively greater time in meetings than their colleagues, as discussed in Section 6.4.[382] In addition, managers have been found to be more satisfied in enclosed offices than secretaries and accountants, who tend to prefer more open arrangements.[78]

The varying nature of the types of work tasks engaged in by different job types, as well as professions, helps explain the different influences of workspace types on different individuals. For example, artistic creativity sometimes benefits less from preparation work tasks than scientific creativity.[80] Furthermore, employee tasks and roles have been found to influence the effects of the physical workspaces on an individual's work performance and well-being.[114] Furthermore, as discussed in Sections 6.2.1 and 6.2.5, an individual's work performance is affected by their interaction with physical environments and stimuli. Thus, the varying work experience of individuals, in terms of time and experience with various workspaces, may influence the effects of physical workspaces on an individual's work performance. Moreover, gender has been found to influence the effects of physical environments on worker performance.[403]

Further research into these topics will aid researchers and design teams in determining the types and quantities of workspace types that should be provided for workers of different job types, gender, professions, and work experience, in terms of maximizing worker performance. For instance, by evaluating the extent to which job type, as well as professions, affects worker performance in different workspace types, the relative value of incorporating these factors into design solutions can be determined. This research can be achieved, in part, by evaluating the effects of various workspace type use rates for workers of different job types on worker performance, as well as the effects of workers of different job types devoting various proportions of work time to different work tasks on worker performance.

§ 6.2.3 Identifying creative work tasks

The creative work process of individuals, groups, and organizations, which are utilized to develop innovations, involves a diverse series of work tasks and cognitive processes.[164, 279] A myriad of creative work process models have been developed over the past century, in order to better understand the innovation process.

§ 6.2.3.1 Existing creative work process models

A number of researchers have organized and evaluated the creative process as a series of stages, while others have investigated both stage based and non-stage based sets of cognitive subprocesses that are involved in creative work processes.[12, 110, 149, 164, 279, 466] In addition, several models have been proposed that integrate stage based models with cognitive subprocesses.[279, 439] For example, Osborne (1963) developed a seven stage creative process model, which involved *Orientation, Preparation, Analysis, Ideation, Incubation, Synthesis, and Evaluation* stages.[348] In contrast, Treffinger (1995) proposed an integrated model, which was comprised of three primary processes: *understanding the problem, generating ideas, and planning for action*. These processes involved a series of subprocesses. *Understanding the problem* involved mess finding, data finding, and problem finding. *Generating ideas* included divergent thinking, elaboration of ideas, and the evaluation of ideas through convergent thinking subprocesses. *Planning for action* was focused on the development and implementation of ideas and concepts through solution finding and acceptance finding subprocesses.[439]

§ 6.2.3.2 Differences and similarities between existing models

Treffinger's model, among others, assumed that the sequence of processes and subprocesses, as well as the duration of each process and number of times each process was revisited, would vary between projects, professions, and individuals.[110, 279, 439] In contrast, a number of the stage based models maintain that the stages are conducted in a fixed sequence.[318, 466]

Nevertheless, the processes and subprocesses involved in the various models do share some similarities. For example, the *Orientation*, *Preparation*, and *Analysis* stages of stage based models are similar to Treffinger's *Understanding the Problem* process and subprocesses, while Osborne's *Ideation*, *Incubation*, and *Synthesis* stages are similar to Treffinger's *Generating Ideas* process. In addition, existing research on subprocesses has provided further clarity into the creative process, and may be complementary to the previously developed creative process stage based models.

For instance, Treffinger, among others, proposed that both convergent and divergent cognitive subprocesses are involved in every stage of the creative process.[279, 318, 439] Convergent processes involve the development of specific, conventional solutions based on logic, existing knowledge and findings, as well as traditional or specific domain oriented perspectives. Divergent processes involve the consideration of problems and solutions from a diverse array of typical and atypical perspectives, and generally lead to a range of alternative answers. Divergent processes incorporate existing knowledge, but also require the development and consideration of unexpected associations, links, and combinations between diverse domains of research and concepts, as well as the transformation of existing information and concepts, into innovative, unforeseen solutions.[164, 318] Generally, divergent processes are necessary to generate novel solutions, as well as to consider problems and solutions from an array of perspectives. Convergent processes, on the other hand, are necessary to explore the risks of introducing innovative solutions, as well as to select and further develop one or more of them.[164, 439]

§ 6.2.3.3 Application potential of existing findings and important future research directions

Thus, a definitive creative phase model has not yet been developed. Furthermore, in order to determine how to maximize the creative performance of individuals, groups, and organizations, it is important for future research to develop a greater understanding of the creative work process and subprocesses, as well as the sequence and variability of the individual work tasks that comprise creative work processes. For instance, there may be optimal combinations and sequences of the various processes and subprocesses for certain tasks, domains, and individuals, and some processes and subprocesses may be more influential than others.[279]

Nevertheless, the potential processes and subprocesses that have been identified by existing research provide an indication of the types and qualities of workspace environments that promote the performance of individuals and groups conducting the various work tasks that are involved in creative work processes. Furthermore, the results of existing literature indicate that different spatial types, spatial qualities, and space resources are beneficial for knowledge workers conducting various work tasks, as discussed in more detail in Section 6.2.4. Thus, the provision of a diversity of workspaces that promote various work tasks are necessary to support the creative performance of knowledge workers. The results of the studies presented in Chapter 7 support this finding. Moreover, further research into developing a more precise creative phase model, as well as research into the types and qualities of workspace environments that promote work performance, such as the studies presented in Chapter 7, can help design teams develop work environments that maximize worker performance.

§ 6.2.4 Performance of different workspaces for various work tasks

There is substantial evidence that worker performance within a specific workspace type differs based on the type of work task being conducted. For example, Amabile & Conti (1999) found that work projects that were rated high in creativity had significantly different physical workspaces from those rated low in creativity.[13] Moreover, extant research indicates that creative employees that work within work environments and organizations that are designed to promote productivity rather than innovation are not able to perform well.[12, 128]

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Furthermore, there are a number of examples in existing research that indicate that the effects of specific workspace types on the performance of workers varies by work task. For instance, conducting complex tasks in isolation has been found to increase task performance, as well as allow creative workers to avoid overstimulation and other environmental stressors associated with non-private workspaces.[52] In support of this finding, working in groups on complex work tasks has been found to reduce worker performance.[318] Indeed, one of the biggest losses of work time is interruptions from colleagues.[114] In contrast, task performance, including speed and accuracy, of employees conducting non-cognitively demanding, simple, and routine work tasks, such as secretarial and administrative work, has been found to increase in the presence of others.[52] Furthermore, workers performing these types of work tasks have been found to have a greater capacity to deal with unexpected social interactions and distractions, without impairing their work performance.[32]

In accordance with these findings, the Yerkes-Dodson Law established an empirical relationship between worker performance, work task difficulty, and the level of mental and physiological stimulation of the worker. This relationship is illustrated in Figure 6.2.[63] For instance, Broadhurst (1959) found that different tasks require different levels of mental and physical arousal to maximize worker performance, depending on the level of cognitive difficulty of the work task. Thus, when workers perform work tasks that demand high levels of concentration, they are most effective when they receive minimal physical and mental stimulation. On the other hand, when employees engage in work tasks that are not cognitively demanding, they perform better with high levels of physical and mental stimulation.[63] Although this study evaluated worker performance for several different work tasks, it is important to note that knowledge workers engage in a much broader range of work tasks, both in groups and as individuals, as discussed in Section 6.2.3.

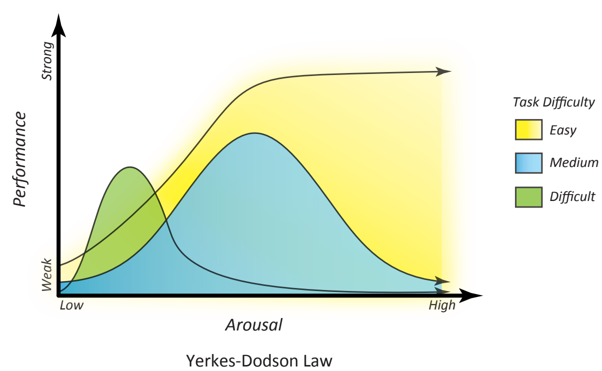

FIGURE 6.2 Worker performance based on task difficulty and mental and physical arousal, a Yerkes-Dodson Law

Thus, the results of the findings presented in this subsection indicate that private workspace types, such as focus rooms and cellular offices, are more appropriate for cognitively demanding work tasks. Furthermore, the general level of influence of physical work environments, as well as the influence of individual workspace types and spatial qualities, on the performance of knowledge workers varies based on the type of work task.[318] In addition, it is apparent that various workspace types are more and less suitable for conducting different work tasks, and thereby affect worker performance.
Therefore, the degree of influence of a wider array of workspace types on a more diverse range of work tasks should be further evaluated, as the cited existing research suggests that worker performance on different work tasks is dependent on the level of physical and mental stimulation the worker receives from colleagues and their contextual environment. Moreover, the results of existing research suggest that the optimal level of stimulation for each work task varies. Therefore, it is important to identify and

evaluate the optimal level of stimulation of various work tasks that are engaged by knowledge workers, in terms of worker performance, both as individuals and groups.

In addition, it is important to develop further investigations into determining the varying effects of different types of stimulation on worker performance, for a diverse range of work tasks. For instance, it is important to identify and evaluate other qualities and resources of the physical environment that also affect worker performance, as discussed in Sections 6.2.5 and 6.2.6, and investigated through the surveys discussed in Chapter 7.

§ 6.2.5 Effects of workspace spatial qualities + resources on worker performance

The work performance and creativity of workers are influenced by the qualities and resources of the workspace types that they inhabit. For example, the perception of workers of the quality of their physical workspaces has been found to influence their perception of the level of support from their business organization, as well as influence their IQ and work performance.[249] Moreover, Dul (2011) found that physical workspaces affect the creative performance of knowledge workers independently from the effects of the social organization.[129] A comprehensive overview of the influences of various qualities and resources of physical work environments on worker performance for various work tasks is outside the scope of this chapter. Davis (2011) and Duffy (1997) provide more extensive reviews of existing literature on this topic. In addition, Dul (2011) reviews and evaluates a number of spatial qualities that have been found to affect worker creativity in existing literature. However, Dul (2011) noted that the relative weight of influence of the individual cited factors was not able to be determined, and that there are surely more physical work environment qualities that influence worker creativity.[129] Nevertheless, the following subsections provide a brief overview of several of the workspace qualities and resources that existing literature indicates are highly influential on worker performance.

§ 6.2.5.1 Design to reduce negative stimuli

Some of the qualities of physical workspaces that knowledge workers typically inhabit have been found to negatively influence their work performance, well-being, and comfort. For instance, typical open floor plan workspaces have been found to cause excessive social interactions and distractions, which in turn perceptually over stimulate the workers, thereby diminishing their work performance.[114, 427] Moreover, existing research on the influence of physical workspaces on worker performance tend to focus on alleviating negative qualities of current workspace types, such as improving poor environmental conditions, including poor thermal, acoustic, and lighting comfort, as well as optimizing the privacy levels of workers.[114, 387] For instance, worker productivity has been found to be reduced when occupants' are thermally uncomfortable.[261, 387]

§ 6.2.5.2 Design to provide positive stimulation

However, alleviating negative qualities of current workspace types may not be the most effective solution for improving worker performance. For instance, the provision of positive physical workspaces

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and spatial qualities has been found to improve worker performance, creative performance, mood, job satisfaction, and well-being.[129, 318, 424] For example, personal interactions with positively stimulating physical workspaces are beneficial for conducting creative work tasks, as well as stimulating for the brain.[12, 318] In addition, the presence of high quality stimuli has been found to result in the generation of greater quantities of ideas during problem solving tasks.[80] Similarly, through a review of existing literature on the effects of physical workspaces on worker creativity, Meusberger (2009) contends that creativity requires specific environmental conditions.[318] For instance, Amabile (1996) determined that physical workspaces that are designed to be cognitively and perceptually stimulating can enhance creativity.[12] Moreover, thinking in broad, open spaces has been found to increase creative performance by 20%, compared to thinking in enclosed, box spaces.[273] Thus, the quality of interactions, availability of necessary work resources, and stimuli of the physical environment affect the creative and worker performance of individuals. It is important to note that despite this evidence, there is relatively little existing literature on the qualities of physical work environments that stimulate creativity.[129]

§ 6.2.5.3 Promoting positive stimuli versus mitigating negative stimuli

Nevertheless, the results of existing literature indicate that positive physical stimuli and environments may have a greater influence than negative stimuli and environments on worker performance and comfort, may make the presence of negative stimuli less influential and more manageable, and can lead to performance gains that are greater than the performance losses incurred by negative stimuli. For instance, knowledge workers that perceive their physical workspaces support creativity have been found to have less environmental discomfort and stress in terms of job satisfaction.[424] Furthermore, Hellinga (2010) found that the presence of views of plants in combination with natural daylight in office workspaces reduced the glare discomfort of building occupants, as well as reduced the artificial light levels that they considered to be adequate to conduct their work. Similarly, a separate study found that participants perceived a forest with 5% of the illuminance level of a nearby urban area as equally bright.[429] Moreover, Mangone (2014) found that the presence of plants in open floor workspaces reduced the occupants' perception of uncomfortable indoor temperatures, as well as improved their comfort at typical temperatures.[293] In addition, Section 6.2.7 presents several further supporting research findings, as well as discusses the potential of design to promote positive attitudes to improve other negative aspects of the lives of workers. Thus, there is evidence that the development of positive physical work environments can increase worker performance, as well as reduce the effects and influence of negative stimuli and negative aspects of physical work environments on worker performance and comfort.

§ 6.2.5.4 Design for worker control over their physical work environment

Furthermore, design strategies that provide occupants with control over potentially negative stimuli have been found to be effective in a number of cases. Environmental control includes the ability of an individual to control specific qualities of their physical workspaces, including the thermal, lighting, and acoustic qualities of their workspaces. Personal control over one's workspace, including environmental control and physical adjustability, has been found to increase job satisfaction, worker performance, communication, privacy, comfort, and satisfaction with the physical environment, and has been linked to improved well-being, productivity, and creativity of workers.[114, 211, 214, 336] In particular, individual control over one's acoustic environment, in terms of noise, has been cited by workers as the factor they would most like to be able to control.[268] Moreover, noise is commonly the most cited issue open plan workers cite for causing dissatisfaction with their physical workspace.[427] Furthermore, the preferred level of visual and acoustic privacy of occupants has been found to vary based on their current work task and job type, as discussed in Section 6.2.2. In addition, in terms of design for occupant control over their environment, it is important to note that knowledge workers require different tools and resources, as well as levels and qualities of stimulation, privacy, and other spatial qualities for optimally performing different work tasks, as discussed in Section 6.2.4.[63, 114, 129, 318]

§ 6.2.5.5 Incorporate spatial qualities that promote the work task being conducted

As discussed in Section 6.2.4, existing literature indicates that spatial qualities have different effects on the performance of workers conducting various types of tasks. For example, working in an open space, compared to working in an enclosed space, has been found to improve the creative problem solving skills of occupants.[273] Thus, it is important for design teams to account for the effects of various spatial qualities on the performance of workers conducting the tasks the workspace type is designed to accommodate. To this end, Section 6.2.4 discusses the level of privacy and general level of environmental stimulation occupants prefer while conducting several work tasks, Chapter 7 discusses the results of several studies that explored the effects of various types of spatial qualities on the abilities of workers to conduct a range of work tasks, and Section 6.2.5.7 discusses the value of further research into the effects of spatial qualities on conducting various work tasks, including several promising future research areas.

§ 6.2.5.6 Account for the (variable) degree of influence of various spatial qualities on worker performance

It is important for design teams to take into account the potential that different qualities and stimuli within workspaces, both positive and negative, have different degrees of influence on worker performance. For example, research in the field of Attention Restoration Theory (ART) indicates that watching television, playing video games, socializing in an urban plaza or cafe, and attending sports venues help reduce stress and restore direct attention. However, personal interaction with natural environments, such as parks and forests, have been found to be considerably more effective at reducing stress and restoring direct attention, among other benefits. This finding was determined to be true both in terms of the quantity of time necessary for individuals to benefit from the restorative environment, as well as the quantity of stress reduction and increase in direct attention the participants gained.[241, 418] Moreover, natural stimuli have been found to be particularly effective at improving worker performance and comfort.[49, 204, 254, 339] Thus, some stimuli are more effective and efficient at improving worker performance and comfort than others.

Moreover, there is evidence in existing literature that some stimuli have a variable effect on worker performance, depending on the other stimuli present in the physical workspace, among other factors. Furthermore, existing research indicates that some stimuli have an effect only in combination with certain other stimuli and spatial qualities. For example, Hellinga (2010) found that the presence of natural daylight improved the visual comfort of workers, and reduced their glare discomfort, when they were provided a view of vegetation. In contrast, natural daylight was found not to have an effect on workers' visual comfort and glare discomfort when they did not have a view of vegetation.[204] Hence, seemingly non-influential work environment factors, such as the effect of the presence of plants on occupants' visual comfort, may also influence worker performance when combined with other workspace qualities.

§ 6.2.5.7 Further research on high performance workspace stimuli and spatial qualities

However, there is limited existing research on the relative value of various inherent and potential spatial qualities of physical workspaces, in terms of their influence on worker performance. To this end, the surveys discussed in Chapter 7 explore the potential value of a number of spatial qualities, in terms of their influence on the ability of knowledge workers to conduct various work tasks. Moreover, the results of existing literature indicate that further research into the degree of influence of various spatial qualities on worker performance, as well as the potential negative and positive effects of various combinations of diverse stimuli on worker performance, can yield important results. Furthermore, this type of research can help identify and evaluate the relative influence of potential high quality spatial qualities that have not been previously considered.

It is important to note that the results of existing literature indicate that there is substantial need, and value, for future investigations into identifying and evaluating potentially effective positive spatial qualities. For instance, the extent and scope of possible ways that various positive spatial qualities and workspaces can reduce the effects of negative physical workspaces and stimuli has not yet been explored, and may yield a number of effective design strategies and solutions. Furthermore, based on the evidence discussed in this chapter, it is conceivable that the development of positive workspace types may also reduce the effects of negative social-organizational work environment stimuli and external stressors on worker performance. However, further research is necessary to determine these potential effects and effective design solutions.

§ 6.2.6 Influence of primes on creativity

Existing studies have found evidence that physical environments and stimuli may act as primes, or figurative cues. Primes, in turn, have been found to influence people's behavior, as well as their creative and job performance.[155, 187] Priming occurs when individuals begin to unconsciously associate specific environments and stimuli with either positive or negative reactions, based on previous experiences.[155] For example, when workers perceive that working in a specific workspace type improves their creativity based on previous experiences working in such a space, their creative performance is improved. Furthermore, when workers are informed, or have pre-existing knowledge, that a certain stimuli or space improves their creativity, their creativity can also be improved when they are within this type of space or in proximity to the stimuli.[155] In addition, if individuals have an overall positive experience in a space, they have been found to feel more positive, creative, and motivated when they return to the space. In contrast, if they have a negative experience in a certain place, they may project negative emotions and fears onto these spaces when they return to them.[318]

Therefore, the design of physical work environments generates primes for workers, and can thereby improve their work performance. This can be achieved when these environments are developed to remind people of previous positive experiences, generate new positive experiences, or are perceived to be designed to promote creativity, comfort, productivity, and well-being. The provision of adaptable workspace, on the other hand, may generate negative associations or inhibit positive associations.

For example, if a garden space is associated with being away from work, but is over time used as a brainstorming workspace, the garden, and possibly vegetated space types in general, may no longer be positively associated with being away from work by the occupants.

Further research is necessary to determine the implications of these potential effects, as well as to determine what types of spaces and stimuli employees associate with stimulating creativity and improving worker performance. For instance, extant research, as well as discussions with the participants of the study presented in Chapter 7, indicate that people perceive plants and access to daylight as improving their overall job performance.[204, 293]

§ 6.2.7 Influence of emotional state on creativity

Existing literature indicates that the current emotional state of individuals can affect their work performance. For instance, there are a number of existing studies that have found evidence that individuals that are more stressed benefit more from restorative environments than less stressed individuals.[274, 352, 360] Thus, it is important for the design of work environments to consider how physical environments can positively influence the emotional state of occupants, particularly when the occupants are experiencing negative emotional states.

§ 6.2.7.1 Design for happiness

To this end, the development of work environments that promote happy, positive, and healthy employees has been found to increase worker performance. For example, a positive mood has been associated with creativity.[129] This may be because when an employee is in a positive mood, they tend to notice stimuli in the physical environment that they would normally overlook, and interpret these stimuli in a new way based on their current emotions, thereby improving their creativity.[318] Furthermore, happy workers have been found to have superior work outcomes than their more negative minded coworkers, including greater creativity, increased productivity, higher quality of work, and higher income.[56, 133]

In addition, a number of environmental factors that contribute to occupant well-being have also been found to affect the creativity and productivity of workers. For example, Shalley et al. (2000) found that work environments that foster creativity inherently improve the well-being of employees in regards to job satisfaction and turnover rates.[401] Furthermore, knowledge workers with higher self-efficacy, or belief in their capability to perform a specific task, have been found to have better worker performance.[185] As discussed in Section 6.2.5, various positive physical workspaces and stimuli have been found to increase employee motivation, self-esteem, and job satisfaction, and thereby self-efficacy.

Similar to the discussion in Section 6.2.5.3, environments that promote positive attitudes help individuals overcome other negative aspects of their life, as well as improve their work performance. For instance, employees with higher self-efficacy have been found to be able to block inhibiting effects and stimuli of the contextual physical and organizational work environment.[185] Moreover, higher self-efficacy also contributes to an employee's intrinsic motivation.[185] These findings are important because an individual's creativity has been found to peak when they have primarily intrinsic motivation that is developed from challenging work tasks, an interest and curiosity in problem solving, and being satisfied and enjoying their work.[318] Furthermore, low self-esteem has been found to lower the creative and work performance of knowledge workers.[318] Thus, providing positive physical work environments that promote worker satisfaction, self-efficacy, comfort, and well-being, as well as increase workers' perception of support from the business organization, may contribute to intrinsic motivation, thereby improving their creative performance. Furthermore, the design of spatial environments that promote healthy, positive workers inherently improves their creative performance, and vice versa. In addition, in regards to the discussion in Section 6.2.5.3, these findings provide further evidence that design for positive workspaces can be more effective than alleviating negative stimuli.

§ 6.3 Design for innovative, high performing workspace types

Unfortunately, existing literature does not provide a clear understanding of the performance of different physical workspace types and spatial qualities on different work tasks, as discussed in Sections 6.2.4 and 6.2.5. This issue has led to the development of generalized, ineffective workspace type design solutions. Further research is thus necessary to identify and evaluate potential high performance workspace types. To this end, the following subsections explore potential high performance workspace types, as well as high performance workspace type design guidelines and performance parameters, based on the results of existing literature.

§ 6.3.1 Design for novel workspace types

Although relatively little research has been conducted on the topic, existing literature from numerous research domains provides some evidence that can aid researchers and design teams in identifying and evaluating novel, high performing workspace types. For instance, creative people have been found to feel the need to seek out unfamiliar situations that allow for greater access to new experiences and perspectives.[401] These types of experiences, in turn, remind and inspire individuals to consider their own problems from new perspectives. Furthermore, individual interactions with unusual physical environments, such as forests in a building, have been found to foster unusual mental associations, which promote the reconfiguration of components of ideas, objects, and behaviors into new arrangements. These processes have been found to improve creativity, as well as reduce stress.[199, 290] Thus, these findings suggest that the design and integration of novel, unfamiliar spatial environments into office buildings can promote creativity.

However, it is important to note that repeated exposure to an unusual physical environment may, over time, generate a feeling of familiarity by the inhabitants, as well as attenuate the effects of the environmental stimuli on the inhabitant. This would, in turn, render the perception of the environment as a typical, no longer unusual, less stimulating environment. This altered perception would negate the original novelty benefits of the now familiar environment and stimuli. Indeed, the emotional effects of various positive and negative stimuli on people have been found to diminish over time, although the rate and scale of this diminishing effect has been found to depend on the type of stimuli. This phenomenon is referred to as hedonic adaptation.[158, 357]

Although existing research on hedonic adaptation of physical environments is relatively scarce, there are a number of existing findings that can aid design teams in the design of physical environments that mitigate hedonic adaptation. For instance, existing research indicates that hedonic adaptation enables people to adjust to low quality physical environments. For example, urban dwellers over time have been found to adjust to areas of increased levels of air and light pollution, and consider them acceptable.[24] Although there has not been much research on the hedonic adaptation of individuals towards high quality and novel physical environments, several general methods to mitigate positive hedonic adaptation have been identified and evaluated in existing literature. For instance, the rate of an individual's hedonic adaptation to a positive stimuli can be reduced if their exposure to the stimuli occurs dynamically and at varying time intervals. Furthermore, novel and surprising experiences are more likely to capture people's attention and trigger their memories and thought processes. Indeed, experiences and stimuli that individuals continually think about, and are aware of, are less prone to hedonic adaptation. To this end, it is important to consider that existing literature suggests that people need to remain aware of the attributes of a space that make it different from other spaces, in order to reduce their hedonic adaptation to the spatial environment.[158, 285] Therefore, individuals should be perpetually reminded of the contrasting qualities between positively stimulating environments and lower quality environments, in terms of promoting various work tasks, in order to maintain their perception of the novelty and value of the space. This will in turn reduce the effects of hedonic adaptation.

It is important to note that this design strategy is not promoting the incorporation of low and high quality workspace types into office environments. Rather, it is important to consider that different workspace types are beneficial for different work tasks, as discussed in Section 6.2.4. Therefore, the occupation of various workspace types will remind workers of the value of each type of workspace for different work tasks. Thus, if workers inhabit a range of diverse physical workspaces, this diversity of environments and spatial qualities may reduce the effects of positive hedonic adaptation, as well as promote individuals to reconsider their tasks and ideas from different work perspectives, even if the individual spaces are eventually no longer perceived as novel. Furthermore, the occupation of different environments may encourage individuals to discontinue or reconsider routine behaviors and other habits, thereby promoting them to consider their actions from new perspectives. Thus, further research should be conducted to determine the potential of these effects on worker creativity. To this end, the potential effects of the strategic combination of various physical work environments on worker performance are discussed in more detail in Section 6.4.

Taken together, the findings discussed in this subsection indicate that the identification and development of innovative physical workspace types should not rely solely on the *newness* of an environment to achieve worker performance goals. To this end, the following subsections discuss a number of other design strategies that existing literature indicates can promote worker performance.

§ 6.3.2 Design for adaptable workspace types

Workspace types that can be fluidly occupied, and allow effective multitasking by responding to rapidly changing workspace resource and quality needs and conditions, can improve worker performance. This is because adaptable workspaces can be designed to provide effective environments for multiple work tasks, thereby increasing the space efficiency and multi-tasking potential of the environment. Adaptable workspace types also reduce the need for workers to move from one physical environment to another, which has been found to cause workers to switch attention and tasks, as well as become distracted from work.[323] These factors are important because work tasks and job types typically shift throughout the day, week, month, and year, as discussed in Section 6.4.

Furthermore, dynamic, adaptable physical workspaces may support an individual's perception that a space is novel. For example, the qualities of daylight, and its interaction with the elements of a physical workspace, vary throughout the course of a given day and by season. These types of dynamic stimuli may prolong the perception of novelty of a space by individuals. Further research is necessary to determine the potential effects of various adaptive, dynamic work environments.

§ 6.3.3 Design to accommodate current + future building + work infrastructure

Another current issue of workspace types is that most existing types were developed before the transition to digital work environments. Some traditional incompatibilities of certain work tasks may now be eliminated. For example, workers can conduct research while in meetings via wireless internet.[323] Moreover, the design of workspaces based on their ability to promote the use of current and innovative work tools and systems may lead to alterations of existing workspace types, such as open floor workspaces, as well as the development of more innovative and effective workspace types.

§ 6.3.4 Design for dynamic workspace types

As discussed at the beginning of this section, physical spaces can promote creativity if they are designed in ways that foster unusual mental associations and reconfigurations of ideas, objects, and behaviors. In addition, unique, dynamic, and adaptive workspace types, such as natural environments, can improve the creativity of occupants, if they challenge occupants to reinterpret and understand the functions and qualities of the physical environment, as well as their possible interactions with the environment, from multiple perspectives and in new ways. These types of environments can inherently help train individuals to consider problems and issues in novel, unexpected ways.[199, 290]

For instance, design teams can develop workspace types that promote people to consider problems from new perspectives, such as by providing opportunities to perceive the physical environment, as well as social and physical interactions, in innovative and intriguing ways. For example, an interior space could be designed to generate sound from an outside breeze, thereby causing occupants to perceive a connection between sound and movement that they had not previously considered. Alternating lighting strategies can generate varying perceptions of the depth and quality of a space, which can stimulate occupants to repeatedly redefine their sense of scale. In addition, conducting a task in a microforest that is within an office will cause occupants to develop their work tasks in a different environment than they typically conduct their work tasks in, which may promote the development of different thought processes, problem solving strategies, and solutions. Furthermore, a combination of diverse experiences and interactions, particularly in different order over time, such as reading in an open floor workspace, then brainstorming in a microforest, then reflecting on various ideas in a cave, may also promote creative processes. The potential of the combination of experiences in various spaces and via different interactions are discussed in Section 6.4.

Thus, the results of existing literature indicate that there are considerable opportunities to develop novel, high quality workspace types that improve worker performance. Moreover, workspace types that are dynamic, adaptable, and provide optimal resources and qualities for multiple work tasks can improve worker performance, as well as the efficiency and effectiveness of the physical workplace. The next subsection explores in greater detail the potential of a workspace type that existing literature indicates can be particularly beneficial for worker performance: microforests.

§ 6.3.5 Exploring the potential of microforests to function as high performing workspace types

The evolutionary development of humans may provide some promising opportunities for identifying high performing workspace types. Humans have evolved through interactions with sensually stimulating natural environments and processes for millions of years. Research in various scientific disciplines, such as environmental psychology and neuroplasticity, have determined that these interactions with the inherent dynamic and sensually stimulating character of natural environments required adaptive human responses, and were essential to the evolution of humanity's physical, emotional, problem solving, critical thinking, and constructive abilities that are fundamental to human health, maturation, creativity, and productivity.[48, 241, 246, 296]

In comparison, typical work environments lack the beneficial positive stimulation and interactions that natural environments provide, thereby reducing the potential performance of the office workers. For instance, walking freely through a space has been found to improve an individual's creative problem solving skills more than walking in straight lines, such as hallways.[273] Repeatedly walking through the same hallway to one's workspace does not require the worker to think about their path, determine how to orient themselves, or observe or interact with their environment. This type of low quality spatial interaction promotes workers to develop habitual, non-stimulating, almost mechanical ways of moving through their office environments, as well as reduces their performance potential.

In contrast, walking through a forest requires one to continually observe and interact with their ever changing surroundings and fascination stimuli, as well as develop creative solutions to obstacles. As discussed in Section 6.3.1, environments that stimulate workers to change their habits and routines, reconsider problems from new perspectives, and provide positive stimulation have been found to improve creativity.[199, 290] Furthermore, interactions with natural biota have been found to inherently benefit worker performance, as well as individual well-being and comfort, in research conducted by a variety of scientific disciplines and cultures throughout the world. For example, researchers have found that plants can improve worker productivity between 10-15%, and increase creativity by 11-30%.[47, 228, 278, 298, 339] In addition, the presence of plants has been found to improve occupants' overall comfort, as well as thermal comfort, space use rates, and their perceptions of the quality of their environments, including greater air quality, acoustics, and visual comfort and light levels.[45, 146, 204, 228, 423, 462] Furthermore, Vink (2008) found that knowledge workers occupied a garden lounge space 16.9% more than a typical office lounge space, even though the garden space did not provide seating. Moreover, occupants of the garden space conversed 20.6% less than occupants of the typical lounge space, yet the percentage of conversations that were work related were greater in the garden space.[44] Thus, gardens were found to be preferred by occupants, as well as increase occupant use rates of informal meetings spaces, even when more comfortable lounge spaces were available. These findings also suggest that the occupation of natural environments can encourage and lead to greater work focus in conversations in informal meetings. Furthermore, these results indicate that vegetation may not function as a distraction stimulus, but rather as a positive stimulus, even during cognitively demanding tasks.

Indeed, office workers have been found to benefit from, and desire, interactions with natural environments. For example, business organizations have found that when they involve their employees in managing wildlife habitat within the office site, employee turnover is reduced, and employee commitment to the company is improved.[77] In addition, Kaplan (2007) found that employees desired a high probability of interactions with wildlife within the office site.[239]

Furthermore, research in the field of Attention Restoration Theory (ART) has found that natural environments function well as restorative environments, and in doing so, provide stress relief and restore occupants' direct attention.[49, 199] Restorative environments have been found to reduce stress by providing fascinating stimuli in a coherent manner and snapping one out of direct attention.[241, 418] In addition, occupants' perception of the quality of a space has been found to improve if the space is developed as a restorative environment. In fact, restorative environments are perceived by occupants as high quality, more useful, restorative, stress reducing, and compatible with occupants' needs.[241, 418] Thus, restorative environments encourage higher space use rates.

Restorative environments have also been found to improve employee productivity, creativity, mental and physical health, illness recovery time, reduce worker absenteeism, and stimulate individuals to participate in mental, social and physical health programs, such as losing weight, music lessons, and volunteer work.[49, 241, 418] Moreover, restorative environments have been found to be heavily desired by building occupants. Despite these benefits, highly restorative environments are significantly lacking in urban environments throughout the world.[418] Furthermore, although the general qualities of physical environments that are necessary to generating a restorative environment have been identified and evaluated, such as *being away, fascination stimuli, miniaturization, and coherency,* the results of existing literature do not allow for the effective evaluation of the performance of various physical environments as restorative environments. For example, the relative effectiveness of a meadow compared to a more traditional park space cannot yet be determined

Nevertheless, recent research projects have begun to evaluate the performance of various types of natural environments in a manner that allows design teams, researchers, and business organizations to assess the performance of various design solutions and physical work environments. For example, Fuller (2007) determined that parks with greater plant diversity provided greater psychological benefits to occupants than more monoculture parks.[163] In addition, plant diversity, including diversity of bright colors and green areas, were preferred for meadows by Swiss visitors of a botanical garden.[276] Furthermore, research indicates that direct, personal interactions with nature in a spatial environment, such as walking in a forest, are more beneficial than indirect interactions, such as noticing a green wall while walking through a corridor.[4, 233]

§ 6.3.6 Further research into high performance workspace types

It is important to note that the results of existing research indicate that there is substantial potential to develop higher performing workspace types than currently exist, as the discussions in this section demonstrate. Thus, it is important for design teams and future research to develop a diverse range of innovative workspace types and spatial qualities, and explore their potential performance benefits. For example, in Athens, Greece during the 2004 Olympics, the Howler Yoon Architecture practice

TOC

developed an interactive field of artificial light as a public circulation space. The individual lights within the field were activated when people passed through the space. The addition of this type of fascination stimuli to a circulation hallway may further improve the creativity of occupants, as well as provide a restoration effect, by generating sensuous interactions between the movement of individuals and fascination stimuli.[296]

Moreover, further research into the benefits of various quantities and qualities of natural environments, as well as various types of interactions of workers with natural environments, is necessary to effectively develop high performing physical workspace types, as well as to evaluate the effects of various design solutions on worker performance. To this end, the results of the surveys discussed in Chapter 7 may aid the identification and evaluation of potential high performance workspace types. In addition, the existing findings and performance parameters discussed in this section provide general design guidelines for design teams, as well as identify general potentially promising directions for future research studies.

§ 6.4 Design for diverse workspace types

§ 6.4.1 General benefits of providing diverse workspace types

Office building work environments are comprised of individual workspace types, such as conference rooms, lounge areas, open floor workspaces, and cellular offices. As discussed in Sections 6.2.4 and 6.3, there is substantive evidence that indicates that providing knowledge workers access to a diverse array of physical work environments is beneficial to their work performance and creativity. For example, a literature review of the effects of physical work environments on creative performance by Meusburger (2009) found evidence to support the theory that a combination of group work activities, which provide stimulation and diverse perspectives, and individual work activities, which provide solitude and a lack of stimulation, may improve the creativity of workers. The provision of a diversity of experiences (physical environments) has also been found to improve creativity.[318] As discussed in Section 6.3, a diversity of experiences may provoke individuals to consider issues from new perspectives, thereby improving their creativity. Moreover, providing a range of physical work environments may reduce an individual's hedonic adaptation to the various stimuli of different work environments. Similarly, employee autonomy, the degree to which a task provides freedom, independence, and discretion in determining the methods for conducting a given task and control over ones' work, has been found to be important to creative people, and to affect their work and creative performance.[185, 318] Indeed, Amabile and Gryskiewicz (1987) determined that the most frequently mentioned factor in low creativity among knowledge workers was a lack of freedom, while the most frequently mentioned work context factor characterizing high creativity events was having freedom.[185] Therefore, the degree to which an individual has control over the setting where they conduct their work contributes to their creative performance. Furthermore, the ability of a worker to select an appropriate workspace type for a given task is integral to employee freedom, by contributing to a perceived sense of control and ownership over one's work, and is facilitated by providing a diverse range of workspace types, or work experiences.[185]

In addition, as discussed in Section 6.2.1, the personality traits of creative individuals, such as having wide-ranging interests, a pre-disposition to the integration of diverse stimuli, and urges to seek self-fulfillment in a unique manner of their own choosing, indicate that creative people benefit from, and have a preference for, having access to a diverse range of high quality physical workspaces.[318] Furthermore, as discussed in Section 6.3.4, the tasks and job types of knowledge workers frequently vary, which makes the provision of diverse workspace types particularly important for promoting worker performance. Indeed, Duffy (1997) found that providing a variety of physical workspace types resulted in higher performing and satisfied workers.[127]

However, the effects of the provision of various combinations and quantities of physical work environments, and the interrelationships of various work environments, on worker performance, has received relatively little attention in existing literature. Nevertheless, the results found in existing literature demonstrate the importance of this research topic. For instance, Vink (2008) found that providing too many concentration rooms diminishes worker creative performance, but increases privacy and productivity.[462] This effect may be because too many concentration rooms may promote employees to work in solitude, and may also reduce collaboration and interaction, which has been found to reduce worker creativity.[69] Similarly, it is important to consider that the provision of diverse workspace types for promoting various work tasks may prove inefficient for workers and building organizations in some contexts. For instance, it may be possible to provide too many workspace types in an office environment, which will require additional overall workspace, and may reduce worker task efficiency and performance, by causing occupants to move too frequently between different workspaces for different work tasks. Thus, the optimal quantity of different physical workspace types is dependent on the type and rate of tasks being engaged by the building occupants, as well as the organization's worker performance goals.

§ 6.4.2 Determining effective proportions and quantities of specific workspace types

The identification of the amount of time knowledge workers spend on different work tasks is necessary to help determine the quantities and workspace types to include in an overall office environment, in terms of maximizing worker performance. Furthermore, the evaluation of proportions of time spent on different work tasks on worker performance may also provide valuable insight and design guidelines.

For instance, Davis et al. (2010) found that 70% of workers within an office in England spent at least 40% of their time in workspace types other than their individual workstations. Most of their away time was spent in formal and informal meeting spaces.[115] However, it is important to note that time spent on solo tasks and more collaborative activities has been found to sometimes vary widely between individuals with similar job types.[37] For example, Robinson (2012) conducted a review of existing research on the amount of time knowledge workers spend on different tasks, as well as presented the results of observations and surveys of 78 knowledge workers. These research methods were used to evaluate the amount of time the participants spent on different work tasks. The results indicate that knowledge workers spend at least 30-40% of their time on collaborative work tasks. Furthermore, face to face meetings, although occurring at equal frequency as telephone and email meetings, were found to be more satisfying for workers. Therefore, providing high quality physical meeting workspaces that promote workers to engage in physical meetings can improve worker satisfaction, and thereby performance.[382]

Thus, existing research indicates that knowledge workers frequently undertake a range of tasks, that these tasks may be undertaken in different work spaces, and that the combinations of tasks and spaces are likely to vary between individual workers.[114] However, to the extent of the author's knowledge, extant literature has not yet taken into account the interrelationships between the types of available workspaces within office environments and the amount of time workers spend on different work tasks. These interrelationships are particularly relevant to the currently popular 'new' and 'flex' office environment design solutions, as effective relative proportions and quantities of different workspace types that are provided in place of typical private workspaces have not been evaluated in existing literature, yet these design factors clearly have a substantial effect on worker performance.

§ 6.4.3 Effects of proximity and interconnectedness of specific workspace types

In addition, the physical organization and structure of different workspace types within the overall office environment, in terms of their relative location and accessibility to each other, has been found to affect worker performance. For example, the provision of a mix of different meeting spaces close to the typical open floor workspaces of workers has been found to increase unplanned meetings and unexpected interactions, thereby encouraging team communications and collaboration.[306] Furthermore, this combination strategy may reduce the quantity of meetings occurring at open workspaces, which are disruptive to adjacent colleagues.[114]

The way individual workspaces are interconnected can impact worker performance in diverse ways. For example, the siting of specific individual workspace types can be developed in a manner that promotes physical activity. In turn, physical activity has been found to improve worker productivity, task focus, and job satisfaction, while reducing their absenteeism rates and health care costs.[140, 234] Thus, siting different workspace types which are frequently used by employees away from each other, and locating informal meeting spaces along the circulation route between these spaces, may thereby improve worker performance. To this end, informal meetings and spending time in social spaces have been found to help knowledge workers foster wider interactions, improve creative performance, collaboration, job satisfaction, and productivity.[69]

§ 6.4.4 Potential interrelationships + effects of various combinations of diverse workspace types

Thus, it is clear from the results of existing literature that the composition and siting of individual workspace types within overall office environments have an effect on worker performance. However, further research on these issues is necessary to develop design solutions that effectively address these issues. To this end, further research into the quantity of time spent in different workspace types by knowledge workers, and the type of work conducted in these workspaces, may help identify optimal workspace types for different tasks, as well as the relative quantities and proportions of different workspace types that offices should provide to maximize worker performance. Moreover, further research into the potential interrelationships of available workspace types, space use rates, work task rates, and worker performance, such as potentially beneficial strategic methods of siting and interconnecting individual workspace types, may yield novel, effective strategies to improve worker performance.

However, it is important to note that analyses of the effects of providing only the highest performing workspace types may not take into account potential benefits that seemingly low performing workspace types may provide when these workspaces are combined with other workspace types. In other words, the potential benefits of workspace types may not be able to be fully understood if they are only studied in isolation. In certain cases, the performance of workspace types may be greater when interconnected to other workspace types. Therefore, based on the evidence presented in this chapter, further research into the potential interrelationships and effects of various combinations of diverse workspace types may lead to significant insight into how to improve worker performance.

§ 6.5 Chapter Conclusion

Thus, it is apparent that physical office environments affect the performance of knowledge workers in diverse ways. For instance, there are a myriad of design issues that existing workspace types do not adequately address, and which design teams should take into account when developing office environments, in order to improve worker performance, as discussed in Section 6.2. To this end, this chapter has identified a number of office environment design strategies and solutions that can help improve worker performance. In addition, the results of existing literature indicate that previously unconsidered design solutions, including innovative space types and qualities, can improve worker performance, in terms of a broad range of work tasks. For instance, existing literature suggests that microforests may increase worker performance for a number of tasks, as discussed in Section 6.3.

Unfortunately, the effects of specific spatial qualities and design characteristics of microforests and other workspace types on worker performance, in terms of conducting a variety of work tasks, are not yet known. To this end, Chapter 7 describes several surveys that were conducted to evaluate the comparative performance of different types of microforest workspace types, as well as more typical office workspace types, on the performance of workers conducting a number of creative and non-creative work tasks. The results of these surveys are intended to aid in the identification of potential high performing workspace types for various work tasks. However, as discussed in Section 6.4, the provision of only high performance workspace types may not be an effective design solution for office buildings. Moreover, the development of effective interrelationships between individual high performance workspace types is also an integral design consideration. Thus, it is important for office building design solutions to be considered from both the microscale, such as individual workspace type design solutions, and the macroscale, such as the interrelationships between individual workspace types. Taken together, the results of this chapter indicate that the exploration of innovative workspace types and combinations of workspace types, can lead to substantial increases in worker performance, and merit further research.

7 Constructing Creativity

Evaluating knowledge worker preferences for various constructed and natural workspace types and spatial qualities, for a range of work

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Introduction

Physical workspaces influence worker performance and well-being in a myriad of ways, as discussed in Chapter 6. For instance, various workspace types are more and less suitable for conducting different work tasks, and thereby affect worker performance and creativity. However, the relative effectiveness of the various workspace types that are commonly present in work environments on improving the performance of occupants, with regards to a diverse range of work tasks, has yet to be evaluated.

In addition, existing research indicates that natural environments may be beneficial spaces for conducting a diverse range of work tasks, as discussed in Chapter 6. However, the relative value of conducting work tasks in natural environments, compared to typical work environments, is still not well understood.

To this end, this chapter reviews the results of several surveys of knowledge workers that were conducted in Delft, The Netherlands in 2012. The primary objective of the studies presented in this chapter was to evaluate the effect of a range of commonly used office workspace types, as well as natural environments, on worker performance, with regards to a diverse range of work tasks that have been identified in existing literature. The results of the analysis includes the identification of the participants' assessment of the best and worst performing physical workspace types for an array of work tasks, an evaluation of the influence of numerous spatial qualities on conducting various work tasks, and the knowledge workers' assessment of the evaluated physical workspace types, in terms of a range of spatial qualities. These results provide insight into the performance of various workspace types, in regards to a variety of work tasks and spatial qualities.

§ 7.1 Materials and methods

§ 7.1.1 General overview of the study

The primary goal of this study was to evaluate the relative value of various existing and innovative workspace types, in terms of promoting the performance of knowledge workers when conducting various work tasks. Moreover, the participants' perception and evaluation of various workspace qualities, in regards to a number of workspace types, was also evaluated. These research questions were evaluated through the development and administration of several semi-structured, questionnaire based surveys to 64 knowledge workers. The surveys included both brief and extended responses. A more detailed review of the methodology of these surveys is outlined in the following subsections

§ 7.1.2 Participant work environment context

The surveys were conducted at the Delft University of Technology Faculty of Architecture and the Built Environment building (BK City) in Delft, The Netherlands, in the fall of 2012. The Faculty of Architecture and the Built Environment was located in a separate building until May 2008, when the building burned down. An existing building on campus, whose construction began in 1917, but due to numerous issues did not have an official occupant until 1948, was subsequently renovated and renamed 'BK City'. In September 2008, the Faculty of Architecture and the Built Environment moved into BK City. The new work environment was designed to provide a variety of workspace types for the faculty, including cellular offices, open floor work spaces, public and private informal meeting spaces, lab rooms, lounges, cafes, and public and private lecture spaces. Thus, the participants of these surveys had experience working in a range of work types.

§ 7.1.3 Participants

The faculty members at BK City are comprised of educators and researchers, and are organized into four departments: Architecture, Architectural Engineering + Technology, Real Estate + Housing, and Urbanism. Since the target job type for this survey was knowledge workers, the research faculty within BK City were categorized as the survey population. In the fall of 2012, there were 126 staff members who were actively involved in research projects and were physically working at BK City, 81 males (64.3%) and 45 females (35.7%). The mean age of the researcher population was 42.1 years (SD=10.72).

For the pilot study, 10 volunteer researchers were interviewed. These volunteers were randomly selected from the researcher population at BK City. There were 7 male participants (70%) and 3 female participants (30%), with a mean age of 37.1 years (SD=11.51).

For the second phase of the study, a stratified sampling approach was employed to enlist participants, in order to ensure that the knowledge workers from the four departments were proportionately represented, as well as to ensure that the participants represented the broad range of perspectives present within BK City.[156] 64 volunteer researchers were interviewed. There were 40 male participants (62.5%) and 24 female participants (37.5%), and their mean age was 41.6 years (SD=11.16).

The participants for the third phase of the study were randomly selected from the participant population of the second phase of the study. 33 volunteer researchers were interviewed, 21 of these participants were male (63.6%), and 12 were female (36.3%). Their mean age was 42.6 years (SD=9.26).

Furthermore, it is important to note that for phase two and three of the study, the distribution of the participants among the four departments was similar to the distribution of the BK City researcher population distribution among the four departments.

§ 7.1.4 Questionnaire development

§ 7.1.4.1 Creative work task selection process

A range of creative and non-creative work tasks that knowledge workers typically conduct have been identified by existing literature, as discussed in Chapter 6. The range of work tasks that were identified and evaluated in this study project, as defined in Table 7.2, were identified based on evidence from an extended literature review. Special attention was given to identifying work tasks that extant research indicates may have different physical work environment requirements. The results of this review included a broad range of creative and non-creative work tasks, including work tasks identified by Olgaye's stage based creative process model, as well as Treffinger's integrated model, among others. [114, 164, 382, 439]

§ 7.1.4.2 Workspace type + image selection process

Based on the results of a literature review, ten different workspace types were identified as being representative of currently available work space types that office environments provide for knowledge workers to conduct various work tasks, as defined in Table 7.1. Five different types of nature space types were included, as defined in Table 7.1, in order to evaluate the influence of different types of natural environments on occupants' work performance, in regards to a range of diverse work tasks. Since the goal of the study was to evaluate the performance of knowledge workers in existing workspace types and nature space types, the initial images that were selected to represent each workspace type were selected based on their representativeness of typical work spaces. Extraordinary workspaces and natural spaces were avoided, such as spaces with excessive colors, flowers, and expensive furniture, in order to reduce the potential of participants to respond to the unique qualities of these extraordinary images, instead of to the qualities of the space type. The perception of the qualities of the selected images, and their representativeness of the intended space types, were then evaluated by the participants during the pilot phase of the study, and were revised, and in some cases replaced, accordingly.

A follow up survey of 33 participants was conducted, which evaluated the participants' perception of ten different spatial qualities in the images through a 7-point Likert scale self-report based survey. The measured spatial qualities, as described in Table 7.3, included the perceived level of noise, light, privacy, fascination stimuli, and naturalness. The results of this survey indicated that the final image set was perceived by the participants as the author intended. The final image set is illustrated in Figures 7.1-7.15.

Furthermore, it is important to note that during the course of the research, it was determined that the third phase space quality valuation survey could be used as a metric to evaluate the participants' perception of various spatial qualities of the images. However, the qualities used in the third phase interview were identified in the first and second phase of the survey, and therefore couldn't be used in the pilot phase, because they were not yet identified. Nevertheless, it is important to note that this could be a useful valuation method in future research projects.


FIGURE 7.1 Open workspace


FIGURE 7.2 Lounge

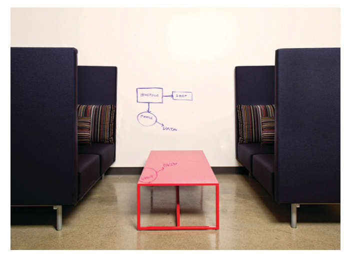
FIGURE 7.3 Informal public meeting

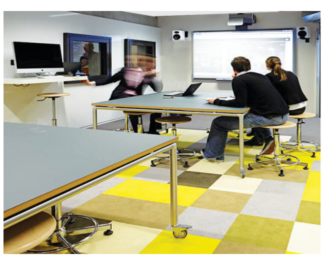
FIGURE 7.4 Lab


FIGURE 7.5 Informal private meeting

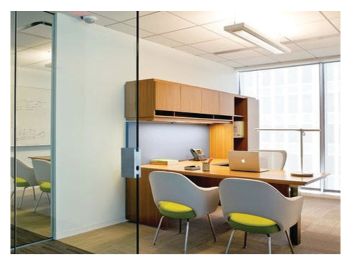
FIGURE 7.6 Cellular office


FIGURE 7.7 Forest amphitheatre


FIGURE 7.8 Meadow


FIGURE 7.9 Dense forest

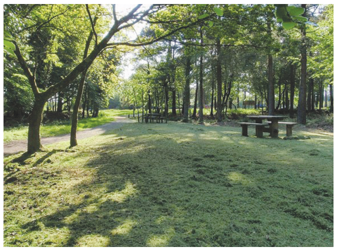
FIGURE 7.10 Park


FIGURE 7.11 Formal meeting


FIGURE 7.12 Lecture hall


FIGURE 7.13 Cave


FIGURE 7.14 Gym


FIGURE 7.15 Cafe

§ 7.1.5 Study method

The study was conducted in three phases, which included a pilot survey, a workspace type valuation survey, and a spatial quality validation survey of the evaluated space types. The specific methods for each phase of the study are described in the following subsections.

§ 7.1.5.1 Phase One: Pilot survey

In the pilot survey, the volunteers participated in the original version of the questionnaire that was subsequently used in the second phase of the study. It is important to note that the pilot survey version requested more in-depth feedback on participant responses for each question, for several reasons. First, the extensive feedback allowed for the authors to evaluate the extent to which the participants perceived the instructions, questions, space types, and survey as the author intended. Second, the in-depth feedback provided a more qualitative comprehension of the participants' decision making processes, as well as their perception of the spatial types and qualities. The pilot survey also allowed for the identification of the average quantity of time that was necessary to conduct the interview, as well as provided opportunities to streamline the interview process. In the first pilot survey, the interview times ranged from one hour to 2.5 hours, depending on the extent of each participant's feedback. The questionnaire was revised based on participant feedback. Afterwards, five of the original participants were randomly selected to participate in the interview again, as well as five new participants, in order to determine if the revisions effectively resolved the issues found in the first phase of the pilot survey. Both the original and new participants completed the revised survey considerably quicker, between 30 minutes to one hour. The participants' responses and feedback confirmed the revisions resolved the issues with the questionnaire that were identified during the initial pilot survey.

The questionnaire began with the participants first being given pictures of the fifteen workspace types, and then being asked to arrange the pictures in order, from the space they would most prefer to occupy in general to the least. The participants were advised to spend one to two minutes on this task. The purpose of this exercise was for participants to familiarize themselves with the image set, since it was observed in the first round of the pilot survey that participants didn't notice self-reported influential spatial qualities of some of the images until the second question. Based on the participants' feedback, the addition of this exercise in the second pilot survey corrected this issue.

Following the image orientation exercise, the participants were given some instructions before conducting the next part of the study. For each work task, the participants were asked to consider the nature and typical work spaces as being equally accessible from their current location. In addition, the participants were instructed to consider the nature spaces to be comfortable to occupy, similar to a warm, spring day, without glare issues, temperature issues, or excessive winds. The nature spaces were to be considered as providing access to all the necessary facilities, including internet, electricity, secretary services, bathrooms, etc., and to be able to be furnished with any furniture desired for the specific work task. However, the participants were asked to identify any change in furniture that they desired. These instructions were developed based on the feedback of the participants of the first pilot survey, in order to ensure the participants considered the nature spaces as equally comfortable and accessible as typical workspace types. This was because the goal of the survey was to evaluate the performance potential of nature workspace types within office buildings, so occupants within these natural workspace types would not be subject to adverse weather conditions or lack of availability of resources.

Following these instructions, the participants were then asked to arrange the pictures of the workspace types, from the space they believed they would best be able to conduct the given work task to the space where they would least be able to conduct the work task. This process was repeated for the sixteen work tasks identified in Table 7.1. During the first pilot survey, it was observed that most participants had difficulty ordering the spaces after they identified the four or five best and worst performing spaces. Several participants reported that after identifying the four or five best and worst spaces, the remaining spaces were very similar in performance. Moreover, for some of the participants, these less important spaces were sometimes perceived as interchangeable, in terms of their potential to promote work performance. These findings are demonstrated by the fact that several participants selected two and sometimes three spaces for the fifth and sixth best and worst spaces for various work tasks. In addition, these participants took the most time to complete the interview. These findings indicate that the degree of accuracy of participant responses after identifying the four best and worst types was relatively less reliable. Thus, the spaces that were not selected for the four best and worst performing were not assigned a value in the analysis of the results presented in this chapter. This method is believed to be the most accurate accounting of the research findings by the author, based on participant feedback and responses. In addition, participants that were asked to order every workspace for each work task, on average, took more than twice as long to answer each question (1 to 2 hours, compared to 30 to 60 minutes). However, it is interesting to note that one participant was able to order all workspaces for each work task without much difficulty or time. Thus, in the second pilot survey, participants were asked to identify the four best and four worst workspace types for each work task. In general, this resulted in significant time savings, and the participants reported clear distinctions in performance between the space types.

Finally, the participants were asked to rate their acoustic preference and privacy preference while conducting each of the work tasks, on a 7-point Likkert scale, ranging from silent to very noisy, and from completely private to very open and public, respectively. The results are shown in Table 7.4.

§ 7.1.5.2 Phase Two: Work Task Space Preference Survey

After revising the interview based on the results of the first phase pilot survey, the work task space preference interview was conducted with 64 knowledge workers. It is important to note that a number of the participants that were contacted had initial reservations to participate due to personal time constraints. Therefore, several instructions were altered for phase two, in order to balance obtaining a high participation rate and the quality of the survey. In phase two, participants were asked to verbalize their main reasons for their overall space selections for each task while they made their selections, instead of providing in-depth descriptions of their decision process. Furthermore, throughout the survey, each participant was randomly asked the reasons for some of their selections, in order to gain a better understanding of why participants made their selections, while maintaining a manageable time duration for the survey. Some participants provided more detailed feedback voluntarily, and without adding to the duration of their survey. Also, two or three participants were able to order all the workspaces for each work task from best to worst, in approximately the same time as other participants ordered the four best and worst space types. The second phase survey took approximately 30-50 minutes per participant, depending on individual response time.

§ 7.1.5.3 Phase Three: Space Quality Valuation Survey

In the third phase of the study, participants were asked to evaluate the different space types used in the first and second phase, in terms of various spatial qualities. The spatial qualities included in the third phase of the study were qualities that participants in the first and second phase identified as important to their space selections, as well as qualities identified in existing research as important to affecting the performance of knowledge workers for different work tasks, such as privacy and acoustic levels, as discussed in Chapter 6. Participants were asked to rate their perception of each workspace type based on individual spatial qualities, on a 7-point Likkert scale, as described in Table 7.3.
The presentation order of the workspace types to the participants were randomly changed throughout each survey, in order to reduce potential order bias. This survey took approximately five to ten minutes for participants to complete, depending on the individual.

§ 7.1.6 Participant performance measurement method

The effects of the various workspace types on the participants' ability to conduct various work tasks was measured through a self-report based survey. To this end, it is important to note that knowledge workers have a unique perspective of their subtle interactions with their physical and social work environment that affect their personal work performance.[129] Supervisor evaluations could provide another level of validation, in terms of assessing the effects of different physical workspaces on the participants' performance. However, without direct access to the workers' cognitive processes and behaviors, supervisors, facility managers, and co-workers are not able to comprehensively perceive the positive and negative effects of the social and physical work environment on their work task performance and creativity.[401] Furthermore, self-reported creativity has been previously correlated to supervisor-reported creativity.[26] Nevertheless, future research should evaluate the performance of knowledge workers in the various workspace types evaluated in this study. However, this type of evaluation was outside the scope of this research project.

The development and use of a semi-structured questionnaire provided opportunities to gain insights into the participants' experiences, thoughts, and behaviors, in regards to the influence of the physical work environment on their work performance for a variety of tasks. This self-report method has several inherent weaknesses. For example, the surveys can be susceptible to common method bias and social desirability bias.[129, 382] However, the potential for these biases was reduced by informing the participants that there were no right or wrong answers, and that their responses were anonymous. They were also told that the goal of the study was not to prove a hypotheses, but rather to learn what kind of environments improve and reduce their work performance for different work tasks. Furthermore, by allowing respondents to expand upon their responses, the author was able to further assess if the participants' responses were being influenced by other biases. For instance, the pilot phase allowed the author to identify and correct potentially leading questions.[382]

§ 7.2 Results and Discussion

§ 7.2.1 Overall results

Overall, the forest space types, *n1-n4*, were preferred considerably more than traditional office workspaces, as illustrated in Figure 7.16 and Tables 7.1 and 7.2. For instance, in Table 7.1, the dense forest space, *n1*, was preferred more than the other evaluated spaces for four work tasks, and second most for six tasks, as shown in row 1 of Table 7.1.

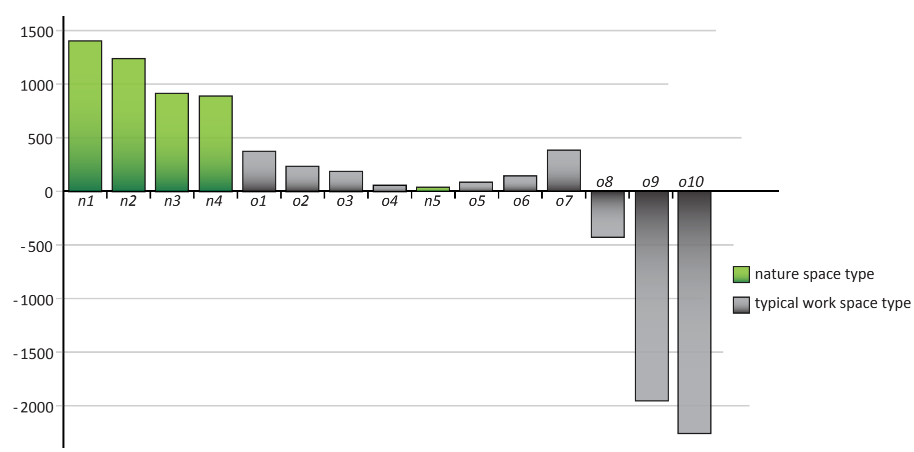

FIGURE 7.16 Participants' overall space type preference

***Note**: Space type definitions: n1=dense forest; n2=meadow ; n3=park ; n4=forest amphitheater; n5=cave; o1=lounge; o2=informal_public; o3=cellular office; o4=informal_private; o5=conference rm; o6=openfloor workspace; o7=lab; o8=café; o9=lecture; o10=gym*

In terms of individual work tasks, forest space types were perceived as the most beneficial work type for 70% of the evaluated work tasks, and at least one forest type was within the four most preferred space types for every work task. In addition, all of the forest space types were preferred more than typical workspace types for a range of work tasks, as shown in Table 7.2. For instance, with regards to group brainstorm tasks, the participants' preferred the four forest spaces more than the office workspaces, as shown in column 5 of Table 7.2. However, none of the forest space types were the highest rated space type for individual and group focus work, administrative work, formal meetings, and for conducting group evaluations, as illustrated in Table 7.2. Nevertheless, the forest space types, particularly the dense forest space type, were among the most preferred workspaces for these tasks as well.

In regards to typical office workspace types, the cellular office, openfloor workspace, and conference room were the only typical workspace types to be rated as the best space type for some work tasks by the participants, as shown in Table 7.1. Furthermore, these workspace types were also ranked within the four most preferred space types for several work tasks, although not to the extent of the forest space types. The lounge, lab, and informal open workspace were also among the four highest rated space types for several work tasks. However, it is important to note that unlike the forest space types, every office workspace type, other than the lounge and private informal space type, were consistently among the worst rated spaces for at least several work tasks as well, as illustrated in Table 7.1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
n1	4	6	3	2	0	0	0	0	0	0	0	0	0	0	0	0
n2	4	5	1	1	1	1	1	1	0	0	0	0	0	0	0	0
n3	0	0	3	7	3	0	1	1	0	0	0	0	0	0	0	0
n4	2	1	3	3	0	2	1	0	1	0	1	0	1	0	0	0
o1	0	0	2	0	5	0	4	1	1	0	0	1	0	0	1	0
o2	0	0	0	1	1	5	2	4	1	1	0	0	0	0	0	0
o3	2	1	0	0	2	0	1	1	0	1	1	2	1	3	0	0
o4	0	0	0	1	0	3	0	1	3	3	1	2	0	1	0	0
n5	0	0	0	0	1	3	1	1	0	3	2	3	1	0	0	0
o5	2	1	0	0	1	0	1	1	0	0	3	0	2	3	1	0
o6	1	1	1	0	0	0	0	0	1	2	2	4	3	0	0	0
o7	0	0	2	0	1	0	0	0	1	1	3	2	2	3	0	0
o8	0	0	0	0	0	1	2	0	0	1	1	1	4	5	0	0
o9	0	0	0	0	0	0	0	0	0	0	1	0	0	0	8	6
o10	0	0	0	0	0	0	0	0	0	0	0	0	1	0	5	9

TABLE 7.1 Participants' Quantitative Overall Preference of Individual Space Types

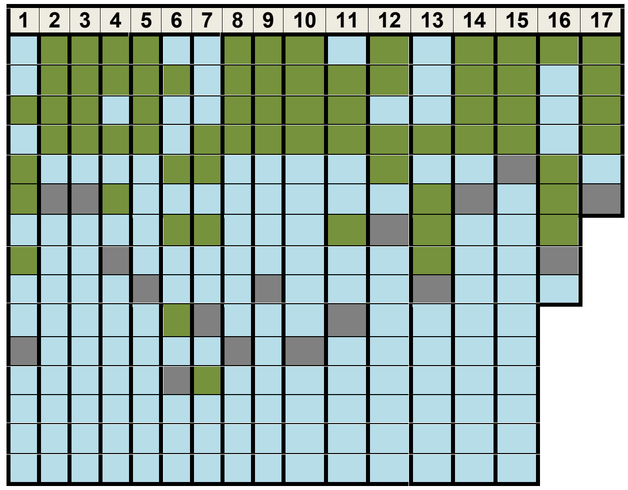

TABLE 7.2 Participants' Quantitative Preference of Space Types per Work Task Type

Note: Work task definitions: (I) = individual task (G) = 2-6 person group task; Administrative/non-technical work(1): email, calendar, etc.; Take a break I(2) G(3): temporary break from work; Brainstorm I (4) G(5): idea generation; Focus/technical work I(6) G(7): complex work tasks, such as technical engineering and design tasks; Reflect I(8) G(9): think about decisions and ideas, but not making decision or judgment; Evaluate I(10) G(11): evaluate ideas + decisions; Informal meeting (12): casual meeting of 2-6 people; Formal meeting (13): official meeting of 2-6 persons; Lunch I(14) G(15): eating lunch; Listen to Lecture(16): 20-50 persons; Gym (17): any exercise activities that can be performed in gym
Note: Work tasks defined and adapted from Robinson 382, Funke 164, and Treffinger 439, among others
Note: Blue cell = typical workspace type; Green cell = forest workspace type; Grey cell = cave workspace type

This may be partly due to the fact that some space types were perceived by the participants to be more appropriate for either individual or group work. Indeed, the comments of the participants corroborate this possibility. For example, a number of participants noted that they considered the conference room to be primarily suitable for group work. However, it should be noted that this observed perception was based on the spatial qualities of the workspace types, and the forest types provided similar scale spaces, as shown in Figures 7.1-7.15, and discussed in Section 7.3.4.4. For example, several participants noted that the dense forest was much like a natural version of a conference room, with similar spatial constraints and privacy levels. Nevertheless, the forest spaces were perceived as providing more useful and accommodating workspace for a broader range of individual and group tasks.

Thus, the results of this study indicate that the development and integration of natural environments into office buildings can reduce project construction and operation costs, as well as increase building space use and efficiency rates, by reducing the quantity of different spaces that need to be constructed and maintained. In other words, by providing workspaces that promote the performance of multiple work tasks, the quantity of individual workspaces for individual work tasks can be reduced for a given project.

Furthermore, if the nature types aren't considered in the analysis, the highest rated spaces for every work task are the cellular office, lounge, openfloor, and conference workspace types. In addition, the café was the highest rated space type for group lunches. When using this analysis method, these spaces also make up the majority of the four highest rated space types for conducting every work task, excluding listening to a lecture and exercising. These results suggest that the other typical workspace types are less necessary. For example, the results indicate that lounge spaces, as well as informal meeting spaces, could be effective substitutes for a dedicated café space, as these space types are more preferred than cafes for every work task. However, as discussed in Chapter 6, existing research indicates that the diversity and quantity of available space types may also impact worker performance.[127, 185, 318, 462] Indeed, informal public and private meeting spaces, as well as lab space, are

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consistently among the second and third highest rated space types for several work tasks, and may therefore provide support spaces that have an adverse effect on worker performance when absent. Hence, further research is necessary to determine the effects of various work space type combinations and quantities on worker performance.

§ 7.2.2 Specific space type results

Space Type discussions

Although an in-depth evaluation of the participants' workspace selections for individual work tasks, and the conclusions that can be drawn from them, is outside of the scope of this chapter, an overview of several space types, as well as several key findings, is presented to provide a summary of the results of the study.

§ 7.2.2.1 Specific forest space type preference

Most preferred forest space type

Overall, the dense forest space type was the most preferred space type, as illustrated in Figure 7.16 and Table 7.1. Specifically, the dense forest space type was the most preferred space type for four work tasks. Moreover, for every work task where a typical workspace type was most preferred, the dense forest space type was the most preferred forest space type. In addition, the dense forest space type was ranked among the top five space types of every work task. These results indicate that dense forest space types can provide adaptable, multifunctional workspaces that have high use rates. Furthermore, they can increase the space efficiency and quality of office environments, as well as worker performance, as discussed in Chapter 6. However, it is important to note that the other forest space types were perceived as more beneficial for a number of work tasks. This finding suggests that a diversity of forest space types would be the most beneficial design solution for an office environment.

Least preferred forest space type

The forest park space and forest amphitheater space types were the least beneficial forest space types, depending on the evaluation criteria. For example, the forest park type was the highest rated space type only for the physical exercise task. In contrast, the amphitheater space type was the highest rated space type for three work tasks, while the dense forest space type and meadow space types were rated as the best space type for four work tasks. In addition, the park space type was the second highest rated forest space type only for administrative work and individual focus work. However, the park space type was never negatively rated, while the amphitheater was negatively rated for individual and group focus work. Nevertheless, it is interesting to note that these space types were still overall ranked higher than the highest ranked typical workspace types, and were consistently ranked as more beneficial than typical workspace types. Thus, these results indicate that knowledge workers prefer, and benefit from, a wider variety, and different types of, workspaces than are currently available.

§ 7.2.2.2 Typical workspace type preference

As discussed in Section 7.3.1, the cellular office, open floor, and conference workspace types were perceived as the most beneficial space types for several work tasks, thereby indicating that for a few tasks, certain typical workspace types are higher performing than forest space types. In comparison, the lounge was never rated as the most beneficial space type for any task. However, the lounge was rated as the most beneficial typical workspace type seven times, more than any other typical workspace type. Thus, the lounge was rated as the most beneficial typical workspace type overall, also partly because it was not perceived as negatively influencing any work tasks. These results indicate that lounge spaces have a highly variable role in the office environment, depending on the presence of forest space types.

§ 7.2.2.3 Forest space vs. typical workspace type preference

Furthermore, the results of the study indicate that forest types are perceived to function more effectively than lounge spaces for every work task. This finding suggests that forest space types can be substituted for lounge workspaces, while also supporting other work tasks, in order to maximize worker performance. This substitution would also increase an office environment's space use efficiency and costs. Generally, the results of this study indicate that forest space types can be similarly substituted for several other typical workspace types, including public and private informal meeting spaces, and cafes. However, further research is necessary to determine the effects of removing space types that these results indicate are ineffective, as discussed in Section 7.4.3.

§ 7.2.3 Similar evaluation and reflection task results

During the course of this study, it became apparent that a number of participants considered reflection and evaluation tasks to have the same, or similar, physical environment requirements. Indeed, 70% of participants rated the workspace types in the same order for individual reflection and evaluation tasks. In addition, 41% of participants did the same for group reflection and evaluation tasks. Furthermore, of the participants who didn't select the same spaces for individual reflection and evaluation, a large proportion gave quite similar responses, by changing the order of only a few space types. In addition, reflection and evaluation tasks were the only combination of tasks that the results indicated the participants perceived as requiring the same or similar physical environments.

These results indicate that participants found that the same types of spaces were the best for conducting both individual reflection and evaluation work tasks, while participants found that a different set of space types were best for conducting group reflection and evaluation tasks. Thus, these findings suggest that the same space in an office environment can be used for both individual reflection and evaluation work tasks, thereby increasing the space efficiency of the workplace. Nevertheless, it is important to note that further research is necessary to evaluate the general applicability of these results, as discussed in Section 7.4.

§ 7.2.4 Space quality evaluation results

As discussed in Section 7.2.5, a random subgroup of the second phase participants evaluated the spatial qualities of the different workspace types. The average standard deviation of the ratings of the evaluated spatial qualities was 1.09, while the maximum standard deviation was 1.87. These results indicate that the participants were generally in agreement in terms of the perceived values of the evaluated qualities of the space types. Furthermore, the reported values of the various spatial qualities for the evaluated space types provide validation that the space type images used in the pilot phase and second phase of this study were perceived by the participants to have the spatial qualities that the author intended to be perceived. Similar to the discussion of the results of the second phase of this study, an exhaustive discussion of the conclusions and impacts of the results of this survey on the state of existing literature and office design is outside the scope of this chapter. Nevertheless, an overview of several key findings is presented in the following subsections.

Quality	n1	n2	n3	n4	o1	o2	o3	o4	n5	o5	o6	o7	o8	o9	o11	o12	o13	o10
a	6.18	6.27	6.21	6.15	5.45	4.24	2.79	4.97	5.27	1.52	3.21	3.52	4.73	1.85	2.48	3.00	3.45	5.97
b	2.61	2.55	2.85	3.39	3.61	3.88	2.09	3.24	4.67	2.12	3.91	3.33	5.94	2.27	2.30	3.09	3.21	6.24
c	3.85	4.00	5.00	5.52	3.85	4.06	2.15	3.52	4.97	2.39	4.24	3.24	6.33	5.00	5.24	5.21	5.42	6.42
d	4.42	6.76	4.91	5.70	3.24	4.30	5.36	3.94	1.88	3.88	5.48	3.85	4.33	3.24	3.73	3.91	4.42	4.30
e	6.61	7.00	6.70	6.79	3.64	3.39	4.45	2.67	1.27	3.00	4.88	1.73	2.82	1.03	2.12	1.09	2.21	1.76
f	4.76	6.88	5.91	6.15	3.76	3.61	2.82	3.00	2.27	2.61	4.82	2.21	4.94	3.24	3.82	3.88	4.48	4.39
g	5.42	5.85	5.21	5.82	3.94	2.91	2.79	2.85	4.18	2.06	4.24	2.18	3.24	2.42	3.21	2.03	2.91	2.58
h	3.03	3.42	3.73	3.94	3.94	3.97	2.48	3.09	3.91	2.48	3.70	2.97	5.45	2.36	3.18	3.09	3.73	5.94
i	6.18	6.64	6.06	6.27	5.30	4.21	3.48	4.18	4.45	2.18	3.06	2.15	3.76	2.24	2.94	2.30	3.09	3.94
j	5.79	6.03	6.30	6.55	4.48	3.55	1.64	4.00	5.42	1.67	1.91	2.33	4.48	2.58	2.85	3.58	3.79	6.64
k	6.52	6.88	6.48	5.70	1.76	1.42	1.45	1.58	4.12	1.18	1.64	1.15	1.27	1.06	1.39	1.06	1.39	1.09

TABLE 7.3 Spatial Quality Valuation per Space Type

Note: Space quality definitions (scale = 1-7): (a) formal-informal; (b)Noise level (silent-loud); (c) Privacy level (private-public); (d)Light quantity (dark-bright); (e) light quality (artificial-natural); (f) space size perception (enclosed-open); (g) fascination stimuli (not fascinating-fascinating); (h) distraction (not distracting-distracting); (i) relaxation (not relaxing-relaxing); (j) (office space – not office space); (k) (built environment-natural environment)

§ 7.2.4.1 Participant preference for diversity of spatial qualities

The results of the spatial quality valuation survey indicate that it is necessary for workspace types to be designed to address multiple spatial qualities. For instance, when evaluating the order of the selected space types for most work tasks, it was not possible to identify an individual spatial quality that determined the ranked order of the space types. Specific examples of this finding are discussed in Sections 7.3.4.2 and 7.3.4.3.

There are several possible explanations for this inability to identify individual spatial qualities for the participants' workspace type selections. For instance, the spatial quality that the participants primarily based their space selections on may not have been evaluated in this study. However, as discussed in Section 7.2.5, the selection of the evaluated spatial qualities was based on participant feedback and spatial qualities that have been found to be important for various work tasks in existing literature, which limits the probability that a key spatial quality was absent. Moreover, it is important to consider that the participants' personality, gender, job type, and work experience in different spaces and roles, may influence their performance in different workspace types, as discussed in Chapter 6.

Thus, different knowledge workers may benefit from different spatial qualities. Indeed, the participant feedback indicated these factors had an impact on their decisions. For example, the interviewers noted that some participants, particularly those with managerial positions, stated during the survey that working among other people didn't bother them for administrative or focus work tasks, while other participants, often those with non-managerial positions, noted that they found it difficult to concentrate and/or work around others for both administrative and focus work tasks. However, the effects of the participants' job type on their responses was not quantitatively assessed in this study. Nevertheless, this finding indicates that it is important to assess the effects of the occupants' job type when designing workspace types and these kinds of studies. This result also suggests that different knowledge workers benefit from different types of spatial qualities, as discussed in more detail in sections 7.3.4.2 and 7.3.4.3. Moreover, this feedback may help explain why the cellular office workspace type was considered the best space type for conducting administrative work, while the seemingly contradictory open floor workspace type was considered the second best typical workspace type. This finding may also help explain why the open floor workspace type was rated best for group focus work.

Furthermore, the effects of specific workspace types on the performance of knowledge workers may be due to a number of spatial qualities. For instance, as discussed in Chapter 6, public work space has been found to improve worker performance when conducting administrative tasks,[78] yet the cellular office, a workspace type that was perceived as private, was the highest rated space type for conducting administrative work. Furthermore, several typical workspace types that were perceived as public workspace types were positively rated for administrative work tasks. This finding indicates that either different participants' preferred different levels of privacy, or another spatial quality, a combination of spatial qualities with different weights of influence, or the perception of the overall quality of the space types, were perceived to be more important to improving their work performance. Additional findings that suggest that the influence of workspace types on worker performance are due to multiple spatial qualities are discussed in Sections 7.3.4.2 and 7.3.4.3.

Taken together, these findings support one of the key findings of the second phase survey: it is important to provide a diversity of workspace types in office environments, in order to maximize worker performance. This is because this type of design strategy inherently provides a diversity of spatial qualities. Moreover, these results suggest that the design and evaluation of workspace types for specific work tasks should take into account the individual and combined effects of a number of spatial qualities.

§ 7.2.4.2 Participant preference based on more than one spatial quality

This subsection reviews several key findings of this study that indicate that no single spatial quality determined the participants' preference for specific workspace types for individual work tasks. Hence, these findings also suggest that the effects of workspaces on the performance of occupants on specific work tasks is due to the influence of more than one spatial quality.

Indeed, in terms of brainstorm tasks, as discussed in Chapter 6, open spaces, compared to enclosed spaces, have been found to improve creativity in existing literature.[273] In contrast, the participants selected the dense forest space as the best space type to conduct group and individual brainstorm work tasks. In addition, the meadow, which was rated as the most open space type, as shown in row (f) in Table 7.3, was selected as the fourth best space type for conducting individual brainstorm tasks. Furthermore, for group brainstorm tasks, although the meadow was the second most preferred space type, several workspace types that were perceived as enclosed spaces, such as the conference, lounge, and private informal meeting spaces, were among the highest rated spaces for conducting group brainstorm activities. These results indicate that creative performance is dependent on more than one spatial quality.

To this end, the five highest performing spaces for individual brainstorm tasks were perceived as being highly stimulating, which suggests that it is important for individual brainstorm workspace types to provide fascinating stimuli. Nevertheless, other space types, such as the café, open floor workspace, and cave, were rated poorly for conducting brainstorm tasks individually, even though they were perceived as providing fascination stimuli. Therefore, additional spatial qualities may also influence the effectiveness of workspace types to promote brainstorm work tasks. Indeed, the spaces that were rated as the most relaxing were ranked as the highest performing space types for individual brainstorm tasks, which indicates that a relaxing environment may be important for individual brainstorm tasks.

Privacy may also be an important factor for individuals to conduct brainstorm tasks. For instance, although the dense forest space type was perceived as less open than the meadow, and thereby arguably less conducive for brainstorming, the dense forest space type was perceived to be more private, as shown in Table 7.3. This may have had an effect on the participants' space type preference for brainstorm tasks, since the participants in the second phase survey noted that they preferred a high level of privacy for brainstorm tasks, 1.94 for group brainstorm tasks and 1.59 for individual brainstorm tasks, as shown in Table 7.4. Thus, as discussed in Chapter 6, the effects of various spatial qualities on the task performance of workers may vary based on the type of work task being conducted, as well as the presence and levels of other spatial qualities. Therefore, further research is necessary to determine the motivation behind the participants' selections.

In further support of the finding that the effects of workspace types on work task performance are due to more than one spatial quality, the participants' evaluation of the privacy and acoustic qualities of the highly ranked space types did not agree with their reported preferred privacy and acoustic levels for most work tasks, as illustrated in Tables 7.3 and 7.4. This finding indicates that although privacy and acoustic performance parameters are commonly perceived as central design issues when developing office environments, privacy and acoustics are not the most influential spatial qualities on worker performance for most work tasks, and other factors should be given greater consideration in workspace selection and design processes.

	1				2				3				4				5				6			
	Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy	
	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max
Avg.	2.42	4.64	2.84	4.80	3.19	5.58	3.59	5.86	3.59	5.92	4.09	6.38	1.50	3.06	1.59	3.44	1.97	3.75	1.94	3.70	1.39	2.89	1.33	2.73
Std. Dv.	1.21	1.35	1.42	1.45	1.32	1.37	1.54	1.27	1.20	1.00	1.59	0.95	0.76	1.18	0.83	1.47	1.07	1.20	1.25	1.45	0.55	1.25	0.51	1.06

	7				8				9				10				11				12			
	Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy	
	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max
Avg.	1.72	3.52	1.72	3.42	1.63	3.34	1.63	3.56	1.92	3.83	1.92	3.72	1.61	3.23	1.63	3.38	1.84	3.72	1.81	3.41	2.94	4.95	3.11	5.25
Std. Dv.	0.72	1.10	0.92	1.27	0.77	1.16	0.88	1.38	0.84	1.00	1.07	1.36	0.77	1.05	0.85	1.13	0.88	1.00	0.97	1.31	1.07	1.17	1.25	1.36

	13				14				15				16				17			
	Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy		Acoustic		Privacy	
	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max	pref	max
Avg.	1.77	3.42	1.56	2.95	3.06	5.59	3.28	5.92	3.25	5.69	3.83	6.36	1.38	2.69	1.88	3.72	3.58	5.84	3.20	5.55
Std. Dv.	0.83	1.07	1.01	1.29	1.22	1.53	1.52	1.15	1.31	1.22	1.65	0.95	0.60	0.99	1.18	1.60	1.57	1.22	1.71	1.57

TABLE 7.4 Participant Noise Level and Privacy Preferences for different work tasks

Note: Work task definitions: (I) = individual task (G) = 2-6 person group task; Administrative/non-technical work(1): email, calendar ,etc.; Take a break I(2) G(3): temporary break from work; Brainstorm I (4) G(5): idea generation; Focus/technical work I(6) G(7): complex work tasks, such as technical engineering and design tasks; Reflect I(8) G(9): think about decisions and ideas, but not making decision or judgment; Evaluate I(10) G(11): evaluate ideas + decisions; Informal meeting (12): casual meeting of 2-6 people; Formal meeting (13): official meeting of 2-6 persons; Lunch I(14) G(15): eating lunch; Listen to Lecture(16): 20-50 persons; Gym (17): any exercise activities that can be performed in gym

§ 7.2.4.3 Effective spatial qualities of work break spaces

The results of this study indicate that the most fascinating and relaxing spaces were perceived to be the most beneficial for taking a break from work and going to lunch, both as an individual and with a group. This finding has a number of implications.

For instance, incubation tasks are essential to the creative work process. Incubation tasks occur when one's attention is diverted to other tasks besides the problem they are trying to solve. For example, when one takes a break from work in a way that engages their indirect attention.[164, 279, 439] Interestingly, spaces that have high quality fascination stimuli have been found to engage occupants' indirect attention.[49] Moreover, as discussed in Chapter 6, spending time in nature, as well as in spaces that are away from the office environment, relaxing, and contain fascinating stimuli, have been found to improve occupants' worker performance and restore their direct attention, by engaging their indirect attention.[418] Therefore, since the most relaxing and fascinating spaces, which also were perceived to be non-work environments, were selected for taking a break and going to lunch, these findings indicate that taking a break and going to lunch can be effective tasks for conducting essential creative work tasks, such as engaging in incubation and restorative activities. Moreover, these results support the general finding that the space types that are provided within an office environment affect the creative performance of the occupants.

Furthermore, the gym was rated as not being relaxing or containing fascinating stimuli, even though it was perceived as a highly non-office space type, as shown in Table 7.3. Thus, the fact that the gym space type was ranked low for these tasks suggests that a number of spatial qualities are important to generate an effective work break space type, as opposed to only being perceived as being away from one's office environment. In further support of this finding, the café space was perceived as less of an office environment than most other workspace types, besides the lounge, and yet it was negatively rated for taking a break and going to lunch, and was perceived as not being fascinating or relaxing. In contrast, the lounge was also rated highly for taking a break, and was rated as fascinating and relaxing, as well as perceived as just as much an office environment as the café, as shown in Table 7.3.

§ 7.2.4.4 Relative perceived value of spatial qualities of different natural environments

The cave space type was included in this study in order to help determine the perceived benefits of working in natural environments, compared to typical workspace types. To this end, participant feedback suggested that the cave was perceived as less natural than the forest space types, due to the presence of a wood floor in the cave image, as illustrated in Figures 7.1-7.15. In this regard, as shown in Table 7.3, participants perceived the cave to be a natural, non-office environment, although less natural than the forest spaces. Nevertheless, the cave was not highly rated for any work task, as described in Table 7.1. This finding indicates that the selection of forest space types was based on more than the perception that the forest environments were types of natural environments. Moreover, this result also indicates that the selection of forest space types was not only because forest environments caused occupants to perceive they were away from their workspace. Indeed, the forest space types were perceived as having a number of different spatial qualities than caves. For instance, forest space types were rated as being more relaxing, fascinating, and slightly less distracting than the cave space type, as shown in Table 7.3.

Furthermore, besides the dense forest space, the forest space types were rated as the most open space types, with a mean valuation of 5.91-6.88. Regardless, the dense forest space was also perceived as quite open, 4.76, compared to similar size workspace types, such as the cellular office, which was rated at 2.82. These results indicate that the forest space types were perceived as more open than similarly sized workspace types. In addition, the forest space types were rated as the most fascinating and relaxing space types, which, as discussed in Chapter 6, agrees with existing literature on natural restorative environments, as well as existing literature that has found that natural environments and stimuli promote worker performance, creativity, and well-being.[66, 129, 339] Moreover, the forest space types were also rated as the most informal and non-office space types. However, it is important to note that forest space types that are integrated into office environments may over time no longer be perceived as informal or non-office spaces, as discussed in Chapter 6. Interestingly, the various forest space types were perceived differently in terms of quality and performance, depending on the spatial quality and work task. This finding indicates that the varying qualities of the different forest space types provide different benefits and spatial qualities, and highlights the need to explore the relative value of a diverse range of forest space types, and workspace types in general, in promoting the performance of workers conducting various work tasks.

§ 7.3 Chapter Conclusion

§ 7.3.1 General results

In general, the results of this study suggest that the work performance of knowledge workers can be improved if they are given access to a greater diversity of physical workspace types, as well as innovative workspace types, than are currently provided in office environments. More specifically, the space types and spatial qualities that maximize worker performance vary by work task. Indeed, the results of this study suggest that innovative space types, particularly microforests, can be more effective at maximizing worker performance and creativity than existing workspace types, in regards to a variety of different creative and non-creative work tasks. For instance, forest space types were found to be more preferred than typical office workspace types for the majority of work tasks conducted by knowledge workers. Moreover, the two least preferred forest space types, the forest park space and forest amphitheater space, were still overall preferred more than the most preferred typical workspace types, and were consistently perceived as more beneficial for conducting work tasks than typical workspace types. Furthermore, the results of this study indicate that the participants' space preferences were based on more than one spatial quality. This finding suggests that the design and evaluation of the performance of work space types should incorporate diverse spatial qualities.

§ 7.3.2 Research limitations + further research opportunities

However, it is important to note that this study has several limitations. For instance, a larger sample size, as well as comparisons of the results of this study to the work performance of knowledge workers situated within various space types in real work conditions, are important to evaluate in the future, in terms of developing results that can be generalized. Moreover, the effects of the participants' personalities, gender, work experience, and job type were not thoroughly evaluated, as discussed in Section 7.3.4.1. Nevertheless, the results of this study indicate that future research on the effects of various spatial qualities on worker performance should account for differences between individuals of different personality types, gender, and job type, as well as for different work tasks. Indeed, existing research, such as Carlopio & Gardner (1992), typically hasn't taken into account the effects of the personalities and job types of the participants on their work performance.[78] Further research should address these issues.

In addition, the results of this study highlight the need for further research on the potential influence, value, and benefits of various existing and innovative physical environments and spatial qualities on worker performance. For example, the participants' responses indicate that existing workspace types and office environments are not yet designed to maximize the potential of their occupants for a variety of work tasks, and should be reconsidered, in order to maximize worker performance. Moreover, the results of this study suggest that it is important to investigate the potential value of innovative workspace types, as well as the inherent interrelationships of individual workspace types. More specifically, the results of the study suggest that further research into determining effective design strategies for incorporating natural environments into office buildings can generate workspace types that substantially improve worker performance. However, it is important to consider that the perception of occupying an interior, constructed forest environment as being similar to occupying a natural environment depends on the design of the space.

Furthermore, although the results of this study indicate that forest space types can be substituted for several typical workspace types , further research is necessary to determine the effects of removing space types that these results indicate are ineffective. As discussed in Chapter 6 and Section 7.3.1, these seemingly ineffective space types may provide supporting roles and effects that this study did not take into account.

§ 7.3.3 Application potential of the results of this study

The results of this study suggest that forest workspace types can be developed as adaptable work environments for a range of work tasks, which will improve worker performance and the space efficiency of office environments. Moreover, by providing workspace for multiple tasks, and thereby reducing the quantity of different spaces that need to be constructed and maintained, the provision of forest types can also reduce office construction and maintenance costs. Thus, the results described in this chapter demonstrate that the development and evaluation of innovative physical workspace types for various work tasks has considerable potential to improve worker performance, as well as office building costs.

Furthermore, the findings discussed in this chapter, as well as Chapter 6, can aid organizational and environmental psychologists, office design teams, and human resource departments in evaluating the effectiveness of existing and proposed individual workspace types and overall office environments, as well as identifying potential opportunities to improve the quality and performance of office environments and workspace types. For instance, the results of this study can be used to inform the selection and design of space types and spatial qualities for different work tasks by design teams, and may promote the development of innovative, higher performing and higher quality workspace types, such as microforests.

The incorporation of natural spaces, such as microforests, into office environments can improve not only worker performance, but the ecological integrity of local ecosystems as well, as discussed in the following four chapters.

Ecological Performance Section

Introduction

There is relatively scant existing research on how to design buildings to improve the ecological performance of local ecosystems, as discussed in the following four chapters, despite the growing interest in the construction industry in developing ‘sustainable’ building projects. Moreover, the ecological performance potential of buildings is not yet known. Thus, similar to the worker performance section that identified and explored numerous ways the design of buildings and building spaces can improve worker performance, the following four ecological performance chapters explore the potential of the design of buildings and building spaces to improve the ecological performance of local and global ecosystems. These explorations resulted in the identification of a number of potentially effective design strategies and guidelines, as well as several potentially effective ecological performance metrics and metric systems. It is important to note that in order to determine the potential effects and benefits of individual buildings, and microforests, on the ecological performance of local ecosystems, it is necessary to evaluate the ecological performance of a project’s context at a number of scales, including regional, ecosystem, building, and individual space scales, as discussed in the following four chapters. Furthermore, it is important to evaluate the potential of diverse building and individual space solutions. Therefore, Chapters 8-11 are not explicitly focused on the ecological performance of microforests. Chapters 8-11 investigate the ecological performance of buildings in general, which was necessary to determine the ecological performance potential of microforests. Thus, it is important to understand that the design of microforests provide diverse opportunities to apply the ecological design guidelines, strategies, performance metrics, and space types that are identified and evaluated in this section.

By identifying strategies, space types, and metrics to improve and evaluate the ecological performance of building projects, the results of this section provide opportunities for design teams to develop higher performing building projects, in terms of ecological, social, and economic performance. For example, the exploration of the diverse potential performance benefits that the design of buildings and building spaces can generate, such as the potential building, worker, and ecological performance benefits that are discussed throughout this book, allow design teams to investigate the potential of architecture to contribute to solving diverse social, economic, and ecological problems through the same building project. For instance, by evaluating the potential of architecture to address the economic, social, and ecologic performance of building projects, design teams can generate a more comprehensive understanding of the relative value of various design solutions, identify potential symbiotic interrelationships that can be generated by addressing multiple performance parameters, generate innovative design solutions, as well as develop higher performing design solutions.
The potential of performance based design, in regards to the design of buildings and building spaces in general, as well as specifically in regards to the design of microforests, is discussed in greater detail in Chapter 12.

TOC

8 Constructing Ecological Integrity

Exploring the potential of constructed environments to improve the state of natural ecosystems

§ 8.1 Introduction

§ 8.1.1 Defining ecological integrity

Ecological integrity (EI) is a normative concept that is used to refer to the state, or health, of an ecosystem. The ecological integrity of a natural ecosystem is based on the state of three of its general performance parameters: its composition, structure, and processes, as illustrated in Figure 8.1.[189, 238]

The term ecosystem composition refers to the diversity between and within the plant and animal species in an ecosystem, or the biodiversity of an ecosystem, and is discussed in more in detail in Chapter 11. Biophysical structures are the living and non-living physical components that comprise an ecosystem, while biophysical processes are the natural ecological processes that occur within an ecosystem. The structures and processes within an ecosystem can be collectively referred to as the functions of ecosystems, as discussed in more detail in Chapter 10 and shown in Figure 8.1.[39, 189, 238, 344]

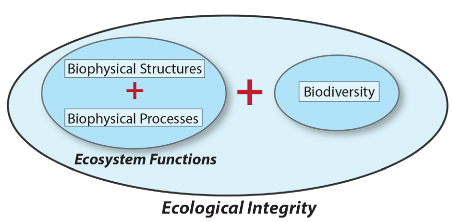

FIGURE 8.1 General properties of ecological integrity of an ecosystem *(based on definitions of ecological integrity by Kandziora (2013)*[26] *and Haines-Young (2010)*[21]*)*

§ 8.1.2 Defining constructed environments and ecosystems

The term constructed environment is similar to the 'constructed habitat' term defined by Mangone (2011), which defined individual buildings as constructed environments that are actively interconnected and interrelated to the local ecosystems.[296] In contrast, constructed environments are defined in this book as more broad ranging, encompassing all individual environments that are constructed by humans, including individual buildings and landscapes.

Similarly, ecosystems that are developed by human communities and activities can be referred to as constructed ecosystems, as defined by Mangone (2011). As discussed in Section 8.2.1 and Table 8.1, as well as illustrated in Figure 8.2, urban areas are comprised of a number of individual constructed ecosystems, such as urban core and suburban ecosystems, which in turn are made up of constructed environments.

§ 8.1.3 Defining the current impact of human communities on natural ecosystems

Natural ecosystems sustain every life supporting function on the planet, including climate regulation, water filtration, and nutrient and energy biogeochemical cycles. The economic value of global ecosystem services was conservatively estimated to be approximately $33 trillion (US) in 1994 by Costanza (1997),[102] and $25 trillion (US) by Patterson (2002).[355] At the national level, the value of the ecosystem services in the Czech Republic were found to be 1.5 times the national GNP.[160] It is important to note that the estimated value of global and national ecosystem services is growing annually through inflation and the increasing scarcity of ecosystem services.[103]

However, current anthropogenic relationships with natural ecosystems are typically parasitic in nature: they negatively impact the ecological, economic, and social performance of local and global ecosystems.[57, 296, 341, 373] For instance, existing studies have determined that every natural ecosystem is now at some risk of modification and degradation by anthropogenic activities.[341] In addition, natural ecosystems in danger of losing their distinct biodiversity and ecological integrity, termed high-risk ecosystems, are becoming increasingly prevalent. High risk ecosystems are found primarily in regions with high human population densities and/or high levels of natural resource exploitation.[257, 341] Furthermore, although pollution and climate change negatively impact natural ecosystems, existing research indicates that direct habitat alteration, including loss, degradation, and fragmentation of habitats, is the primary cause of damaging the ecological integrity and biodiversity of natural ecosystems. Introduced species are an increasingly severe problem, and have been found to be second in importance in a number of studies.[341, 455, 460]

Constructed ecosystems negatively impact natural ecosystems in a myriad of ways, as discussed in Section 8.2.1.3. For instance, the establishment and expansion of urban areas have been identified in a number of studies as one of the most important drivers of direct habitat alteration.[341, 455] For instance, individual buildings within urban core ecosystems typically contribute to these parasitic interrelationships, by negatively impacting the ecological integrity of local natural and constructed ecosystems through their construction and operation processes, as well as through the behavior of the building occupants. Thus, constructed ecosystems, including the human communities and buildings that comprise them, are interlinked to, and directly affect and are affected by, the performance and processes of local and global natural ecosystems, as well as other constructed ecosystems.[296]

These negative interrelationships are unnecessary, and counterproductive. Examples and methods of the development of symbiotic interrelationships between constructed environments and natural ecosystems are becoming increasingly prevalent, and are reviewed in Section 8.3.[174, 281, 384]

§ 8.1.4 Defining the scope of the research

§ 8.1.4.1 Defining the objectives of the research

Identifying effective design strategies to improve the ecological integrity of local and global ecosystems

In order for constructed environments and ecosystems to effectively improve the ecological integrity of local and global ecosystems, it is essential for design teams to be able to determine the most effective methods to improve the ecological integrity of local and global ecosystems. However, effective methods to evaluate the ecological integrity of local and global ecosystems are not yet well developed.[71, 184, 189, 238, 257] Moreover, the identification of effective design solutions, as well as methods to evaluate the relative effectiveness of various design solutions, remains largely unexplored and unresolved.[74, 216, 281, 393, 397]

Thus, the primary objective of this chapter, as well as Chapters 9-11, is to identify and explore how constructed environments, such as individual buildings and landscapes, can improve the ecological integrity of local and global natural ecosystems. Specifically, this chapter provides an overview of the general issues that design teams should consider when developing design solutions for constructed environments, in terms of ecological performance. The three subsequent chapters, Chapters 9-11, are focused on more specific ecological design strategies that existing literature indicates can improve the ecological integrity of ecosystems. Within this book, these specific ecological design strategies are categorized into three types of general ecological design strategies, which together account for the diverse influences of human communities on local and global natural ecosystems: design for ecological behavior (Chapter 9), design for ecosystem functions (Chapter 10), and design for biodiversity (Chapter 11).

However, it is important to consider that the relative influence of these design strategies and ecological performance parameters on the ecological integrity of local and global ecosystems is currently under debate, and is dependent on a myriad of contextual factors, as discussed in the following four chapters. Thus, the exploration of diverse design solutions and ecological performance evaluation methods, from a range of performance based design perspectives, is necessary to determine the relative potential of various design strategies to improve the ecological integrity of local and global ecosystems, as well as to identify and develop effective design solutions, in terms of ecological performance. To this end, Chapters 8-11 contribute to this need for further research in a broad array of research domains in a number of ways, such as through the identification and comparative evaluation of numerous potentially effective ecological design solutions and ecological performance evaluation methods, as well as through the identification of promising future research areas, as discussed in more detail in Sections 8.1.4.2 and 8.4.

§ 8.1.4.2 Defining the research methods utilized in this research project

The discussions in this chapter, as well as in Chapters 9-11, are based on findings from an in-depth systematic review of existing literature, discussions with ecologists, biologists, zoologists, zoo managers, and leading sustainable engineering and design firms, as well as the results of a number of exploratory design case studies that evaluated the potential of mid-size commercial office buildings to contribute to the ecological integrity of local ecosystems, as enumerated in Chapter 1. This diverse research process generated a myriad of research explorations, research and assessment perspectives, as well as validation methods, which improved the breadth, depth, and validity of this research project and the presented findings, as discussed in Chapter 1.

§ 8.1.4.3 Defining the environmental context of the research

The urban core ecosystem, as defined in Section 8.2.1, was selected as the contextual local constructed ecosystem to be evaluated in this chapter, as well as in Chapters 9-11, because it is one of the most challenging and influential building contexts, in terms of developing design solutions that positively contribute to the ecological integrity of local and global natural ecosystems. For instance, building projects within urban core ecosystems typically have limited exterior site areas. Furthermore, infill developments are increasingly eliminating the existing biota in urban core ecosystems, as discussed in Section 8.2.1.3. Due to these factors, among others, urban core ecosystems typically contain the least amount of vegetation, biodiversity, and ecosystem services and functions, compared to other constructed ecosystem types.[10, 183, 308, 455]

§ 8.2 Defining the ecological context of constructed environments

Extant research has determined that solutions for improving the ecological integrity of local natural ecosystems at scales smaller than individual ecosystems, such as at the scale of individual buildings and habitat patches, tend to be most effective when they address the factors that are most important to consider at the ecosystem scale.[257, 341, 393] Therefore, the effects of constructed environments on the ecological integrity of local ecosystems depends on the state of the ecological integrity of the local constructed and natural ecosystems. Moreover, building scale design solutions should be focused on how to effectively contribute to improving the ecological integrity of local natural ecosystems.

It is important to note that there are a number of influential performance parameters that determine the effectiveness of various building scale ecological design solutions within the context of urban core ecosystems, which are discussed in more detail in Section 8.2.2, as well as in Chapters 9-11.

§ 8.2.1 Defining the local ecosystems of constructed environments

Therefore, in order for a building to positively contribute to the ecological integrity of local and global ecosystems, design teams should understand the inherent and potential interrelationships between buildings, building occupants, and local ecosystems, as well as assess the state of local ecosystems. In order to accomplish these tasks, the type and nature of the local constructed and natural ecosystems must be defined. To this end, Sections 8.2.1.1 and 8.2.1.2 provide definitions and evaluations of the typical state of the various types of ecosystems that can be found within urban areas. Moreover, Section 8.2.1.3 provides a more in-depth analysis of the state of typical urban core ecosystems, based on findings from existing literature.

§ 8.2.1.1 Distinguishing between local ecosystem types

An ecosystem categorization method, such as the one shown in Table 1 and discussed in this section, can be used by design teams to identify and obtain a general understanding of the local ecosystems of their building projects. Although an in-depth analysis of the state of the various local ecosystems is necessary, as well as the potential ecological design opportunities and limitations they inherently generate, there is limited existing research on this topic, as discussed in Sections 8.2.1.3 and 8.3.3. Nevertheless, a brief overview of extant research findings is provided in Section 8.2.1.2 and Section 8.2.1.3.

Distinguishing between different types of constructed ecosystems

It is important to note that urban areas (cities) and ecosystems are typically composed of a mosaic of fragmented habitats that differ in their level and pace of transformation from existing natural ecosystems, which are sometimes referred to as pristine ecosystems in existing literature, to urban core ecosystems, as illustrated in Figure 8.2.[257, 308, 338] A number of categorization methods to classify the different types of ecosystems typically present within and around urban areas have been proposed, ranging from existing natural ecosystems to urban-industrial ecosystems. For instance, Kowarik (2011), among others, made distinctions between ecosystem categories based on the varying degrees of transformation of pristine environmental conditions that occur due to urbanization.[154, 257, 338] For example, Kowarik (2011) combined rural, suburban, urban, and industrial ecosystems into one ecosystem type: urban-industrial ecosystems.[257] In contrast, Forman (1986) made a distinction between suburban and urban developments.[15] Indeed, existing research on the ecological integrity of urban ecosystems suggests that rural, suburban, industrial, and urban ecosystems have distinct physical, social, and ecological properties, such as the typical functions, structures, and biodiversity of these types of ecosystems. These differences, which have been found to substantially impact the ecological integrity, functions, and biodiversity of ecosystems, are discussed in more detail in Section 8.2.1.2. Moreover, the different properties of the various types of constructed ecosystems affects the potential opportunities for building projects within these contexts to contribute to the ecological integrity of local and global ecosystems. Therefore, it is important to distinguish, understand, and evaluate the varying ecosystem functions, structures, and compositions of the various constructed and natural ecosystem types. To this end, the ecosystem categorization method proposed in Table 1 and discussed in Section 8.2.1.2 distinguishes the different types of constructed ecosystems that have been identified in existing literature.

Furthermore, it is important to note that these constructed ecosystem types are not mutually exclusive. Patches of different ecosystem types are frequently present within individual constructed ecosystems, as shown in Figure 8.2.[154]

Type of ecosystem	Examples	History	Prevailing level of transformation	Typical Species Richness
Natural	Forests, wetlands, caves	Remnants of natural ecosystems	Low	High
Agricultural	Grasslands, fields	Remnants of man-made ecosystems, resulting from early habitat transformation	Medium	Low-Medium
Horticultural	Parks, gardens, golf course	Transformed remnants or newly established after habitat destruction	Medium to high	Medium-High
Rural	Low density housing	Transformed remnants or newly established after habitat destruction	Medium to high	Medium-High
Suburban	Low-mid density housing, business parks	Typically emerge after habitat destruction	Medium to high	Medium-High
Industrial	Quarry, landfill, factory, transport corridors	Typically emerge after habitat destruction	High	Low - High
Urban Core	High density building areas, city centers	Typically emerge after habitat destruction	High	Low

TABLE 8.1 Different types of constructed and natural ecosystems that occur within urban areas *(adapted from Kowarik (2011)*[257] *and Forman and Godron (1986)*[154] *ecosystem type concepts and tables)*

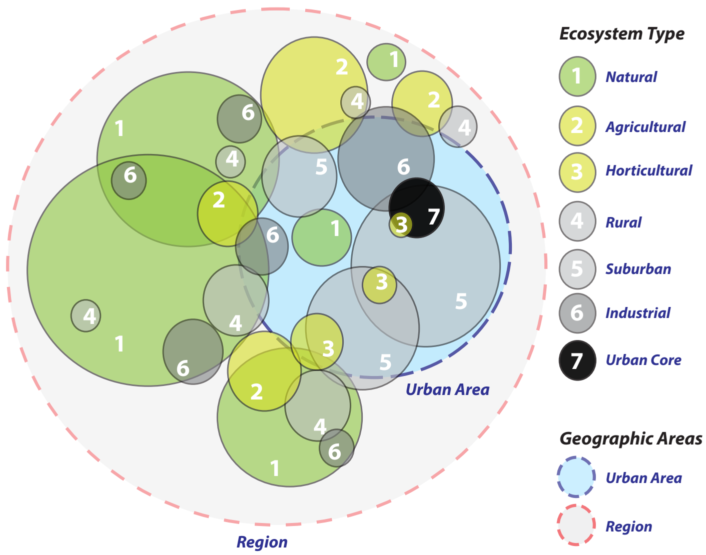

FIGURE 8.2 Spatial diagram of different types of constructed and natural ecosystems that occur within a region

§ 8.2.1.2 Identifying local ecosystem types

Natural (pristine) ecosystems

Natural ecosystems near or within urban areas tend to be fragments of pre-existing and adjacent natural ecosystems.[257, 338] Although several existing studies refer to natural ecosystems as pristine ecosystems, it is important to note that almost every natural ecosystem in the world is being disturbed either directly or indirectly by human activities and developments, as discussed in Section 8.1.2. This has been found to be particularly true for natural ecosystems within or adjacent to urban areas.[257, 281, 338, 341] For example, forests within urban areas tend to experience an increase in introduced species and higher decomposition and nitrification rates than rural forest areas.[308] Therefore, existing research suggests that it is erroneous to refer to natural ecosystems, particularly those close to urban areas, as pristine.

Agricultural ecosystems

Agricultural ecosystems are land use areas that are developed for crops or grazing.[338] Agricultural areas are increasingly experiencing substantial decreases in both generalist and specialist pollinator species. In addition, birds are being displaced from agriculture lands, partly due to a lack of habitat patches being provided in modern monoculture farms. The provision of habitat for bird species within adjacent urban areas has been found to promote the regulation of pests within agriculture ecosystems.[385] Furthermore, in some contexts, adjacent rural and suburban garden areas have been found to be better able to provide suitable habitats for a number of species, including several pollinator species.[75] It is important to note that typical industrial monoculture agricultural ecosystems also tend to have a number of poor performing ecosystem functions, as they have been found to negatively influence local ecosystems in diverse ways, such as by contributing to local flooding and water pollution issues, soil erosion, soil nutrient extraction, and soil compaction.[53]

Horticultural ecosystems

Horticultural ecosystems consist of areas of planted and/or managed native and non-native species, such as large scale parks and gardens, as well as golf courses.[338] It is interesting to note that horticultural ecosystems and habitat patches, even within urban core ecosystems, have been found to have exceptionally high levels of species diversity in some cases, such as in the municipal park of Loppem, Belgium.[206]

A variety of less traditional ecosystem types can also be considered as horticultural ecosystems. For instance, based on the definition of horticultural ecosystems described in this section, ecosystems that are managed to provide ecological services, such as sustainable forest farms, as well as restored ecosystems, can also be defined as horticultural ecosystems. However, it is important to note that existing research indicates that restored ecosystems are less effective in terms of ecosystem functions, services, and biodiversity than existing natural ecosystems.[41]

In addition, brownfield sites and vacant lots have been found to function as habitat patches in similar ways as gardens, parks, and green roofs, although they tend to be less actively maintained, which can be beneficial or detrimental, depending on the intended ecological function of the patch.[257] For instance, a strategic provision of a number of brownfield sites that are left undeveloped and unmaintained for a period of time, within an urban ecosystem, can provide habitats of diverse succession stages, thereby promoting species richness and rare species.[244]

Rural ecosystems: developed from agricultural + natural ecosystems

Rural developments are less dense than suburban developments. For instance, within the US, rural residential developments have approximately 6-25 homes/km^2. In 2000, these exurban developments were the fastest growing form of land use in the US, and covered almost 25% of the land area of the contiguous 48 states. This is nearly 15 times the area of higher density urbanized developments.[65]

Rural ecosystems are typically developed in two general land areas. They are developed around the periphery of cities (UFD), where over time they are transformed into suburban and urban ecosystems as the urban areas expand. Rural ecosystems are also developed in distant areas from cities (RRD), where a number of perceived natural benefits are present, such as outdoor recreation opportunities, privacy, and attractive scenery. The location of RRDs tend to correlate with areas of high biodiversity, due to a demand in similar biophysical features by people and native species.[195] At the same time, the land use area of RRDs in the US have increased five times since 1950.[65] To this end, a substantial portion of existing land area which has been used for forestry, ranching, and agriculture in the past are increasingly being converted to residential sites in the US. Thus, rural ecosystems are being developed both in close and far proximity from urban areas, as illustrated in Figure 8.2.

Both of these types of developments typically reduce local native species richness, as well as the survival and reproduction rates of native spaces near the buildings that are situated within these developments. In addition, these developments tend to introduce exotic species to the local ecosystems. It is important to note that RRDs are more likely than UFDs to be adjacent to national parks and other public lands, thereby having a larger impact on the biodiversity and functions of existing nature reserves and natural ecosystems. Hence, this finding implies that RRDs tend to have a larger ecological impact on local ecosystems than UFDs, although existing research on the ecological impacts of rural developments is currently quite limited.[195]

Suburban ecosystems

Suburban ecosystems typically have a population density between urban and rural levels.[308] Interestingly, suburban residential ecosystems tend to be highly biologically productive, as they typically provide abundant resources for flora and fauna, ornamental fruit and seed plants, and diverse plant species.[28] In addition, residential suburbs have been found to promote exceptionally high levels of species diversity, and can function as ecological corridors and source habitat patches for urban core ecosystems.[206, 410] Indeed, the richness of a number of species has been found to peak in suburban ecosystems, in comparison to adjacent natural, rural, and urban core ecosystems, particularly when adjacent ecosystems are ecologically impoverished.[257, 314]

A number of studies have found evidence that this increase in species richness in suburban ecosystems may be due to an increase of non-native species from rural areas towards the urban core, as well as a decrease in native species from the urban core towards rural ecosystems. In these studies, the suburban ecosystem is the area where the level of declining natives and increasing non-natives combine to generate an overall peak in species richness.[314, 338] However, a number of subsequent studies have found evidence that species richness may not be dependent on a linear urban-rural gradient as previously proposed, but may in fact be more dependent on the specific ecosystem functions and structures, as well as biotic communities, present within ecosystems.[174, 257, 281, 314] From a design perspective, these findings indicate that species richness and diversity are design issues.

Indeed, a number of studies have found that the inherent habitat diversity and spatial heterogeneity of suburban residential ecosystems promotes species richness among a number of species. For example, existing findings indicate that native species can be increased in suburban and urban cores through the design of the environment.[174, 257, 281, 314] For instance, the planting of native vegetation within gardens in the UK was found to significantly increase bird and butterfly diversity, in comparison to non-native gardens.[174] This topic and further examples are discussed in more detail in Chapter 11.

It is important to note that suburban ecosystems can be comprised of both residential and commercial areas, such as business parks. However, business parks tend to have less species richness than suburban residential areas. This is partly because individual buildings within suburban residential areas have individual owners, who have been found to prefer to maintain diverse vegetation landscapes.[174] In contrast, the landscapes that surround individual buildings within suburban commercial and industrial areas are typically designed as a single plan, in which they tend to have a limited variety, and structural diversity, of plant species and habitats.[412]

Nevertheless, business parks provide a number of ecological design opportunities. For instance, buildings within business parks typically are designed with flat roofs, which can function as small habitat patches.[244] In addition, they are often located along transport corridors, such as motorways and main roads, which can make them ideal, in some cases, to function as ecological corridors.[307, 412] Furthermore, business park landscapes typically are intensively managed, incurring high maintenance costs. These landscapes can be designed to provide low maintenance, native vegetation that better promote biodiversity and ecosystem functions.[412] For instance, business park sites can be designed to provide habitat patches of considerable size, through the combination of the exterior site areas of individual buildings.[412] Furthermore, these parks tend to have vacant land areas. These areas typically are not actively maintained, in order to minimize maintenance costs. Interestingly, these areas can provide habitat for pioneer vegetation and animals. Moreover, business parks are relatively undisturbed between dusk and dawn, making them ideal places for nocturnal species, such as amphibians and urban mammals.[173]

Industrial ecosystems

Industrial ecosystems are typically highly disturbed sites, such as wastelands.[338] They normally have coarse, low nutrient or chemically polluted soils, and can be vulnerable to persistent droughts and flooding. Nevertheless, industrial ecosystems have been found to be able to promote high native and non-native species richness, as well as support a number of native rare species.[138, 281] In some cases, they have been found to have greater species richness than local natural ecosystems.[372, 438] This is partly because industrial sites provide optimal habitats for a number of species that may be rare within local natural ecosystems, but are common in the region, such as plants that are tolerant of heavy metals.[281]

Urban Core ecosystems

Urban core ecosystems are the most intensively developed areas of cities. They are often the commercial, cultural, and/or political centers of urban areas.[313, 452] It is important to note that urban areas can contain multiple urban core ecosystems, such as Los Angeles.

Within existing literature, urban core ecosystems are also sometimes referred to as urban ecosystems.[313, 391] Thus, in order to be consistent with existing literature, throughout the remainder of this book, both terms will be used interchangeably to refer to urban core ecosystems. The state of typical urban core ecosystems is discussed in Section 8.2.1.3.

Identifying the Ecological integrity of Typical Urban Core Ecosystems

Limitations of existing research on the ecological integrity of urban core ecosystems

Relatively scant research has been conducted on the ecological integrity of urban core ecosystems, compared to natural ecosystems.[195, 281] Nevertheless, urban ecosystems are gaining increased attention, and there is a substantial quantity of existing studies.[10, 183, 248, 257, 281] However, generalizations of existing results should be considered warily, due to several limiting factors. Existing studies typically fail to account for the effects of the differing spatial and physical characteristics of various urban core ecosystems, such as their physical layouts, development patterns, and infrastructure systems. In addition, existing research has been conducted at varying scales, using a variety of different methodologies, which reduces the comparison potential between different research projects. Furthermore, the majority of existing studies have been focused on Europe and North America, which reduces the generalizability of the findings of these studies.[10, 257, 338] Hence, the complex interrelationships between urban developments and ecosystem dynamics remain poorly understood.[10]

Identifying the ecological integrity of typical urban core ecosystems

Nevertheless, some general insights into the integrity, functions, and biodiversity of typical urban ecosystems are possible. To this end, this subsection provides a brief overview of typical urban core ecosystem conditions. In addition, typical urban core ecosystem conditions, in regards to biodiversity, are discussed in more detail in Chapter 11. Moreover, Section 8.2.2 and Chapter 10 discuss a number of performance parameters that have been found to influence the ecological integrity, functions and biodiversity of urban core ecosystems. In addition, Alberti (2010), Grimm (2008), and Kowarik (2011), among others, provide more detailed reviews of the various factors that typically result from urbanization and affect the integrity, functions, and biodiversity of local ecosystems, such as changes in urban climate, hydrology, and soils, and their associated biotic feedback loops.[10, 183, 257]

Urban core ecosystems tend to disrupt key ecosystem functions and alter existing landscapes and biodiversity patterns, both within the urban area, as well as within local and global natural ecosystems.[257] For instance, there is typically a decline in biodiversity and ecosystem services within densely populated areas as land use intensity increases.[393, 455]

General state of ecosystem functions within urban ecosystems

In terms of the state of ecosystem functions within typical urban core ecosystems, the natural self-repairing capacity of ecosystems is typically exceeded, and ecosystem services are relatively low.[393] Moreover, the demand of ecosystem services by cities throughout the world has been found to be increasing over time, thereby increasingly negatively affecting the ecosystem functions of local and global natural ecosystems.[248, 325] Furthermore, although urban core ecosystems have been cited as inefficient in their consumption of resources, they have been found to be considerably more efficient than other types of constructed ecosystems, such as rural and suburban residential ecosystems, when taking into account the denser quantity of people that inhabit urban core ecosystems (per capita resource demand).[57, 377] Therefore, the effects of the lifestyles and behavior of inhabitants of urban core ecosystems on natural ecosystems tend to be substantially lower than inhabitants of suburban and rural ecosystems. Nevertheless, typical urban core ecosystems, including their inhabitants, substantially negatively influence local and global natural ecosystems in a myriad of ways, as described in Table 1 and Chapters 9-11.

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General state of biodiversity within urban ecosystems

In terms of the state of biodiversity within typical urban core ecosystems, cities are typically established in biodiversity 'hotspots', disturbing key ecological interrelationships and species populations of the pre-existing and local natural ecosystems.[257] Moreover, intensively developed urban core ecosystems typically have the least species diversity rates of any ecosystem type. To this end, the quantity of a variety of species in urban core ecosystems can be less than half that of rural ecosystems.[314] Moreover, urbanization developments in existing urban core ecosystems are currently reducing the proportion of areas dedicated to gardens, trees, and other natural spaces, through infill developments, as well as through the development of newer housing stock with smaller or no gardens than existing housing stock.[57, 75] In addition, urban core ecosystems tend to be highly disturbed matrices, comprised of fragmented habitats with disproportionate quantities and surface areas of early succession habitat patches that are prone to invasive populations.[57, 314] Many urban habitat patches remain at early successional stages due to regular disturbances, such as the mowing of landscapes.[338] These fragmented habitats are commonly mostly inhabited by mobile species, due to less mobile species generally being more sensitive to fragmentation.[257] Due to these factors, open habitat patches are relatively common, in comparison to more mature succession habitat patches.[57] Furthermore, large predators are typically eliminated in urban areas, resulting in increases in mesopredator and herbivore populations. These population increases have been found to reduce plant diversity and disrupt trophic interrelationships, often in unpredictable ways.[195]

Relative (parasitic) ecological similarity of cities

Urban core ecosystems generally have been found to have more species and ecosystem functions in common with other cities than local natural ecosystems. This has led some researchers to consider cities as a global network of similar, immature ecosystems.[314] A number of contributing factors have been identified in existing literature. For instance, typical urban core ecosystems are considered to be immature due to their negative performing ecosystem functions, structures, and communities, such as rapid building development, inefficient use of resources, and lack of resilience.[57] Furthermore, urban core ecosystems tend to have simple food webs, and are dominated by abiotic controls and imported resources, which can lead to the homogenization of ecosystem functions and species among cities.[313] An overview of the typical state of ecosystem services and functions within urban core ecosystems is provided in Table 1.

Although there are a number of similarities between urban core ecosystems, it is important to note that the ecological integrity, functions, and biodiversity of individual urban core ecosystems can vary considerably. For instance, the results of urban area resource demand analyses indicate that the ecological footprint and resource consumption rates of individual cities differ substantially.[23, 33, 36, 44] These variations are due to a myriad of factors, including contextual, temporal, spatial, social, and scalar issues. These issues are discussed in more detail in Chapter 10.

Furthermore, it is important to note that due to the issues discussed in this section and a number of other issues that have been identified in existing literature, urban areas typically have parasitic interrelationships with local and global natural ecosystems.[296]

Regulating Services	Supporting Services	
Filtration/Purification _Increase of pollutants in air, water, + soil[308 425] ***Biological Control*** _Reduced pest regulation[385] _Reduced invasive species resistance[257] _Reduced disease resistance ***Climate Regulation*** _Increased Temperatures (UHI)[425] _Reduced wind flow[425] _Sometimes increased or reduced rainfall[183] _Increased Greenhouse Gas Emissions + smog[455] ***Prevention of disturbance and moderation of extremes*** _Urban areas more prone to extreme disturbances, such as flooding, drought, + erosion[183]	***Soil*** _Urbanization taking place in best soils[9] _Mostly impervious ground surfaces (80% or more)[57] _Urbanization damages soils: _Soil Erosion[425] _Topsoil Removal[425] _Compacted soils[99] _Soil excavation can damage soil horizons + mix topsoil with subsoils[425] _Increased concentration of heavy metals, organic matter, N, P, acids, salts [9, 425] _High soil PH, nitrogen (from concrete + other lime + acidic emissions) [9, 267, 313, 455] _Impervious surfaces kill vegetation, soil organisms, reduces groundwater recharge + increases rate and pollution content of stormwater runoff[425] _Reduced nutrient retention efficiency[183]	***Habitat Provision*** _Vegetation areas in urban core decreasing _Frequent human disturbance from human development + behavior [425] _Typically mostly early succession stage habitats[57, 314] _Early succession stage habitats + disturbed sites attract non-native species[57, 314] _Numerous dispersal barriers, promoting non-native species _Fragmented, diverse, small, edge dominant habitat patches [57, 314] _Open habitats relatively common*57* _Decline in wet and nutrient poor habitats *(results in decline of less common and rare species dependent on these habitats)*[257] _Building and demolishing of buildings creates sudden habitat shifts
Decomposition _Large quantities of organic and inorganic waste produced*57* _Impervious cover reduces biomass decomposition[425] **Provisioning Services** _Urban core ecosystems typically generate few natural resources + consume relatively large quantities of resources[183] **Cultural Services** _Declining due to infill development + reduction of nature area provision in new developments.[75, 455]	***Nutrient + material cycles (biogeochemical processes)*** _Increased Nitrification + nitrate levels in soils, streams, lakes[308, 455] *(increases chance of eutrophication, poor drinking water quality)* _Increased nitrogen, phosphorous discharge and accumulation[308] _Accumulation of metals[183] _Loss of nutrients and minerals via stormwater runoff, nature removal, impervious surfaces, etc. [99, 425] ***Hydrologic Systems*** _Increased surface runoff [9, 99] _Reduced site water infiltration[425] _Lowered groundwater table[307 425] _Increased eutrophication potential[99] _Increased stream sedimentation[99] _Contaminated adjacent waterways[183, 425] _Unintentional water losses substantial portion of water consumption in US cities[30] ***Fixation of solar energy*** _Low primary productivity/plant growth[9, 307]	***Species Maintenance*** _Urban species communities dissimilar to local natural ecosystems, more similar to other cities[313] _Lower species richness in city core[9] _Native flora and fauna decrease[9] _Urban areas typically have high degree of invasive + immigrant species (due to disturbance, dispersal barriers, primary succession environments, human introduction, etc.[9] _Species, often nonnative, preferring nitrogen-rich, warm and dry habitats are overrepresented in cities[257] _Lack of predators results in simplified trophic webs + overabundant mesopredator + herbivore populations[195] _Rare native species become rarer or extinct in urban areas, especially when bound to wet and/or nutrient-poor sites[253, 257] _Animal dispersed plant species overrepresented, due to shiny fruit plants preferred by gardeners, wind dispersal limitations, etc. [4]

TABLE 8.2 Typical Urban Core Ecosystem Functions

§ 8.2.2 Assessing the ecological integrity of local ecosystems

§ 8.2.2.1 Identifying the importance of assessing ecological integrity at the regional scale

The assessment of the ecological integrity of an ecosystem at the individual ecosystem scale typically results in the overestimation of its functions and services, as well as diminishes the valuation and perception of the influence of the other local ecosystems, and other regional scale factors, on the functions and services of an ecosystem.[157] In contrast, a regional scale assessment of the ecological integrity of local ecosystems accounts for influential regional scale factors, such as the myriad of inherent dynamic interrelationships between individual ecosystems, as illustrated in Figure 8.3. For instance, the influence of regional scale ecosystem structure factors, such as the effects of the spatial configurations, geometry, and land cover of individual ecosystems, can be evaluated.[157]

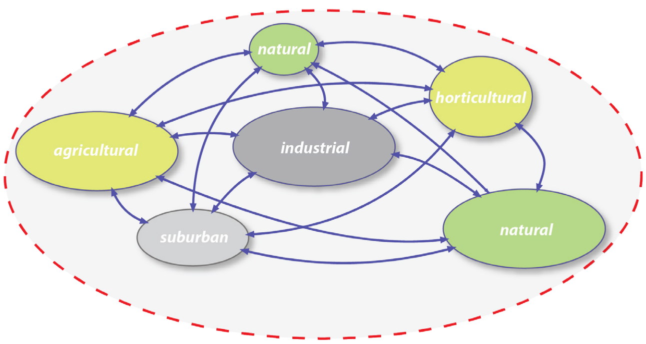

FIGURE 8.3 Visualization of interrelatedness of ecosystems

Thus, the integrity of local constructed and natural ecosystems should be assessed at the larger regional scale, in order to effectively evaluate their ecological integrity and assess their inherent interrelationships. Furthermore, a regional scale assessment of the ecological integrity of local ecosystems allows for the effects of individual constructed ecosystems on local constructed and natural ecosystems to be evaluated. These types of evaluations allow for the identification of the relative impact of various functions of urban core ecosystems on local natural ecosystems, including the issues that are most important to address in order to improve the ecological integrity of local natural ecosystems. Moreover, these types of assessments provide opportunities to identify and evaluate the effectiveness of various design solutions to improve the ecological integrity of local ecosystems, as well as mitigate the negative impacts of urban core ecosystems.

Furthermore, it is important to note that the ecological integrity of local ecosystems are dependent on a number of typological, contextual, social, spatial, scalar, and temporal issues. Therefore, these factors should be accounted for when assessing the ecological integrity of ecosystems.

Section 8.2.2.2 briefly discusses several contextual regional and ecosystem scale factors and interrelationships that should be taken into account. Chapter 10 provides a more comprehensive discussion of the plethora of influential factors that should be taken into account when assessing the ecological integrity of ecosystems, as well as potential methods to assess the functions and integrity of ecosystems.

§ 8.2.2.2 Identifying the impacts of the interrelationships between local constructed and natural ecosystems

Constructed ecosystems impact the ecological integrity of local natural ecosystems in a myriad of direct and indirect ways. For instance, air pollution from cities negatively impact the nutrient cycling and net primary production rates in local ecosystems,[183] and forests within urban areas tend to be more disturbed by human activities.[425] Moreover, the impacts of constructed ecosystems on the ecological integrity of local natural ecosystems, including the state of their ecosystem functions and biodiversity, partially depend on the state of the natural ecosystems. Moreover, local natural ecosystems also influence the ecological integrity of constructed ecosystems, such as by providing habitat patches for specialist species adjacent to urban core ecosystems. This ecological connection provides opportunities for specialist species to inhabit urban core ecosystems, as opposed to the typical generalist species that tend to inhabit urban core ecosystems.[410] Therefore, local ecosystems can both benefit and negatively influence each other. Furthermore, it is integral to understand the interrelationships between local ecosystems, in order to determine the effectiveness of various design solutions.

§ 8.2.3 Assessing the potential of constructed environments to sustain and improve the ecological integrity of local ecosystems

Similar to the discussion in Section 8.2.2, the potential of individual constructed environments to positively contribute to the ecological integrity of the local ecosystems depends on a diverse range of factors. To this end, effective ecological design strategies and solutions, existing and proposed methods to assess the effects of constructed environments on local ecosystems, as well as a number of influential factors that affect the ecological performance of constructed environments, are discussed in Chapter 10 in terms of ecosystem functions, Chapter 9 in terms of the ecological behavior of individuals, and Chapter 11 in terms of biodiversity. Furthermore, the potential of the design of constructed environments to improve the ecological integrity of local ecosystems is discussed in Section 8.3.

§ 8.3 Exploring the potential of design to improve the state of local constructed and natural ecosystems

A growing body of literature is increasingly providing evidence that the typical parasitic interrelationships between constructed and natural ecosystems are unnecessary. For instance, there is substantial evidence that constructed ecosystems can generate symbiotic interrelationships with natural ecosystems. To this end, this section discusses the general types of symbiotic interrelationships between natural and constructed ecosystems that have been identified and evaluated in existing literature.

§ 8.3.1 Potential of urban core ecosystems to sustain and improve the functions of local ecosystems

Urban core ecosystems have the potential to generate a myriad of beneficial ecosystem functions and services, as well as improve existing functions, services, and biodiversity. For example, urban areas have a number of inherent characteristics that can be used to promote ecosystem functions, biodiversity, and ecological behavior. For instance, people can, and do, provide habitat patch maintenance and development, and urban areas contain large concentrations of water, energy, nutrients and climate controlled environments.[174, 248, 426] Moreover, cities typically import and accumulate large quantities of a number of potential resources, such as concrete, N, P, and metals.[216] However, they are commonly treated as waste.[9, 425] These typical urban area waste streams can function as valuable resources. For example, nitrate rich treated wastewater can be used to irrigate crops and lawns, which can mitigate the consumption of commercial N fertilizers.[183]

Moreover, the restoration and maintenance of habitats and functions of natural ecosystems can stimulate local economies. For instance, a study of 50 coastal habitat restoration projects in the United States found that these projects generated substantially more jobs than other traditional industries, including coal, gas, and nuclear industries, and provided long term economic benefits, such as future job creation through the restoration of fisheries and coastal tourism, as well as higher property values, flood protection, and improved water quality.[131] These examples demonstrate the plethora of potential symbiotic interrelationships that can be developed between the diverse industries, infrastructure systems, communities, and natural processes and environments that are typically within and adjacent to urban core ecosystems.

It is also important to note that some seemingly negative typical performance parameters of urban core ecosystems can benefit the functions of local ecosystems, within some contexts. For instance, non-native plant species can increase soil mineralization rates when exposed to urban heat island effects (UHI).[183, 194] Furthermore, UHI can reduce building energy consumption rates in heat load dominated cities.

§ 8.3.2 Potential of urban core ecosystems to sustain and improve the biodiversity of local ecosystems

Furthermore, urban core ecosystems can potentially improve the biodiversity of local ecosystems. For example, there are reports of increasingly rare biota thriving in cities, such as the bumblebee in San Francisco and the suburbs of England, as well as the common frog in England.[174] Moreover, some Red List plant species have been found to be able to establish self-sustaining populations in urban areas. Nevertheless, rare species have been found to become rarer at the city scale.[257] However, at the habitat patch scale, rare species have been found to increase, when appropriate habitat patches are provided for them. For instance, rare species that populate urban core ecosystems are mostly located on sites that do not encounter high intensity development and disturbances, such as city parks and along railway lines.[314] This finding suggests that urban core habitat patches can support rare species if they are designed to minimize human disturbances, as discussed in more detail in Chapter 11. Therefore, these findings suggest that decreases in rare species in urban areas are due to a lack of adequate habitat provision and poor design solutions, in terms of biodiversity performance. Thus, decreases in rare species in urban areas are unnecessary.

In addition to supporting rare species, urban core areas have been found to be able to support native species richness. For example, Italian cities have significantly different urban flora between cities, and most of the species are more similar to local natural ecosystems than other cities in the region. Even in high stress environments, such as paved habitats, a number of Italian cities have high native species richness.[281] Moreover, although species richness in urban core ecosystems are typically less than half that found in rural ecosystems, several manageable factors have been identified as the primary causes.[257, 314, 426, 455] Moreover, existing literature indicates that the development of self-sustaining populations within urban core ecosystems may be more important for supporting biodiversity within local ecosystems than promoting species richness.[257] These design issues, and the potential of urban core ecosystems to support the biodiversity of local ecosystems, are discussed in more detail in Chapter 11.

§ 8.3.3 Limitations of existing research on developing effective ecological design solutions

The relative importance of the individual ecological performance categories, in relation to each other, is currently under considerable debate and remains poorly understood, particularly within the urban context. Furthermore, the value of various performance parameters within and between each performance category, such as the comparative value of individual ecosystem functions, remains difficult to determine.[103, 341, 393] Nevertheless, the lack of existing research and effective analysis tools makes the determination of the most important performance parameters to address for a particular building project difficult. For example, if a building is located within a typical urban core ecosystem, in which ecosystem services and indigenous species richness is low, the comparative value of addressing different ecosystem functions, promoting ecological behavior, and promoting biodiversity can be unclear. Similarly, the inherently interrelated nature of the processes, functions, and biota within and between local and global ecosystems, as discussed in Section 8.2.2, makes the identification and evaluation of the effectiveness of various design solutions difficult. For example, existing studies have found that design solutions that are intended to improve specific ecosystem functions and species within natural ecosystems typically negatively influence other integral ecosystem functions and species.[10] These design issues are discussed in more detail in Chapters 10 and 11.

Furthermore, as discussed in Section 8.2.1.3, the majority of existing research that is focused on improving the ecological integrity of ecosystems has focused on natural areas outside of urban areas.[195] Furthermore, most of the ecological research investigating the impacts of constructed environments and ecosystems has been conducted at the city and large park scale.[393, 486] Unfortunately, there has been even less research conducted at the individual building scale. Indeed, relatively few effective building scale solutions have been identified and evaluated in existing research.[281, 486]

Nevertheless, there is a growing body of research and interest among researchers from diverse research domains on the potential of urban areas to contribute to the ecological integrity of local and global ecosystems. It is important to consider that existing studies typically evaluate urban areas that are not designed to positively impact the ecological integrity of local and global ecosystems.[174, 183] Few researchers have explored the potential of the design of constructed environments within urban areas to improve the ecological integrity of local ecosystems.[20, 58] Nevertheless, as discussed in Sections 8.3.1 and 8.3.2, design decisions within urban core ecosystems can have a positive impact, such as through the development of urban and peri-urban nature reserves and ecological corridors.[30, 32, 49] Thus, the results of existing research indicate that future research investigations on the potential of the design of constructed ecosystems and environments to improve the ecological integrity of local ecosystems may yield substantial results. The ecological potential of the design of constructed environments and ecosystems is discussed in more detail in Section 8.3.4.

§ 8.3.4 Potential future ecological research areas

It is important to consider that the ecological performance of various design solutions for different ecosystem functions and biodiversity targets will likely need to address performance tradeoffs between the various design solutions, as discussed in Section 8.3.3. For instance, although a habitat patch design may provide habitat for more rare species than another solution, it may be less effective in terms of water storage. Thus, in these types of situations, design teams will have to determine which performance goals are most important to address within the local context. However, further research is necessary in order to adequately identify and assess the performance tradeoffs of various design solutions.

Moreover, as discussed in Section 8.3.3, future research projects should investigate the ecological performance of constructed ecosystems and environments that are designed to positively impact the ecological integrity of local and global ecosystems. To this end, the effects of diverse design solutions within the same context should be evaluated, in order to comprehensively explore the potential of ecological design solutions within specific contexts. Moreover, studies that evaluate the positive potential of various ecological performance parameters of constructed ecosystems may provide key insights into how the ecological integrity of local and global ecosystems can be improved through the design of constructed environments, as well as through the design of the constructed ecosystems they are situated within.

§ 8.4 Chapter Conclusion

Thus, the design of urban core ecosystems, including buildings, infrastructure systems, and public spaces, inherently impacts the ecological integrity of local and global ecosystems, regardless of whether design teams consider the ecological performance of their design solutions during the design process. Furthermore, the examples and issues presented in this chapter make it apparent that the performance of the diverse ecological performance parameters that affect the ecological integrity of constructed and natural ecosystems are design issues. In other words, the design of constructed ecosystems and environments can benefit, and negatively impact, local ecosystems in diverse ways, as well as benefit from the development of symbiotic interrelationships with local ecosystems. Moreover, existing research suggests that there is potential for ecological design solutions to effectively mitigate and resolve negatively performing ecological performance parameters of constructed ecosystems.

However, in order to develop effective design solutions, design teams need to identify and evaluate the ecological impacts and possibilities of their design solutions. To this end, the following three ecological chapters explore the potential of the design of human communities to improve the ecological integrity of local ecosystems in more detail, in regards to each of the three general ecological design strategies identified in this book: design for ecological behavior, Chapter 9, design for ecosystem functions, Chapter 10, and design for biodiversity, Chapter 11. These chapters include a review of existing literature from various research domains, in order identify and evaluate effective design solutions and strategies, methods to assess the value of various design strategies, as well as important research gaps. Moreover, potentially effective assessment methods, opportunities, and benefits of simultaneously addressing these three general ecological design strategies are also discussed within these chapters. Taken together, these chapters explore a diverse range of ecological design strategies and evaluation methods that can be effective in developing constructed environments and ecosystems that improve the integrity of local and global ecosystems, while at the same time, improving the quality of local and global human communities.

9 Constructing Ecological Behavior
Exploring the potential of constructed environments to promote diverse ecological behaviors

§ 9.1 Introduction

There are three general design strategies for improving the ecological integrity of ecosystems, as discussed in Chapter 8. To this end, this chapter explores the potential of the design of constructed environments to promote ecological behavior.

§ 9.1.1 Defining the current typical state of ecological awareness of human communities

The majority of people's interactions with natural ecosystems, biota, and processes occur within urban areas.[391] Moreover, the proportion of people's interactions with nature that take place in urban areas is continuing to increase, in concert with the increase in the global rate of urbanization.[452, 453] However, the quantity of human interactions with nature in urban areas is currently decreasing, which is resulting in an 'extinction of experience'.[369]

For instance, existing green spaces within urban core ecosystems are being removed through infill developments.[75] Indeed, urban area developments have some of the greatest local extinction rates in the US, and frequently eliminate a substantial majority of native species.[314] Moreover, the natural environments in urban areas that most people experience in their daily lives are typically highly cultivated and homogenous, such as ornamental grass lawns. Repeated interaction with these low quality and non-stimulating environments has been found to contribute to the perception that nature is unimportant and not integral to people's lives.[320] This effect is usually most extreme within urban core ecosystems, where species richness and vegetation cover is typically very low.[455]

Furthermore, the majority of the ecological processes that sustain human societies, and the adverse effects of societies' current parasitic interactions with natural ecosystems and processes, are typically located outside of the communities we inhabit, hidden from view and experience.[257] There is evidence that this increasing collective disassociation and ignorance of human communities about natural processes, systems, environments, and the negative effects of human communities on local ecosystems, promotes collective indifference.[320, 368] This adverse effect is also supported by existing research that has found that individual interactions with natural environments in one's everyday life are a major determinant of an individual's sensitivity to environmental issues.[383, 391, 399]

In other words, people value nature less as they become more disassociated with nature. Their awareness that natural and human ecosystems are interdependent is weakened, as well as their awareness of the negative effects of their resource consumption. Moreover, their awareness that the exploitation and removal of natural processes and ecosystems diminishes the performance and quality of constructed ecosystems is also diminished.

This '*constructed separation*' between humanity and nature has severe consequences, including the ever-burgeoning ecosystem service footprints of constructed ecosystems that are threatening the sustainability of local and global economies and communities.[296]

§ 9.1.2 Identifying the potential of design to promote ecological behavior

The results of extant research that has investigated the effectiveness of various activities to promote ecological behavior, such as ecological education and restoration programs, attention restoration activities, resource consumption activities, and recreational activities, among others, indicates that effectively promoting a diverse range of ecological behaviors is much more complex than solely focusing on improving the ecological awareness of individuals and communities. For instance, even individuals who have a general concern for the environment do not inherently display greater ecological behavior than their peers, in regards to a diverse range of specific ecological behaviors.[145, 236, 237, 419] Indeed, existing literature indicates that design solutions must address specific ecological behaviors, rather than focus on raising general ecological awareness. [86, 95, 145, 198, 237, 430] Moreover, in order to effectively improve the ecological integrity of local and global ecosystems, it is imperative that local communities actively engage in a diverse range of specific ecological behaviors, as discussed in Sections 9.1.1 and 9.2.2, as well as Chapters 8 and 10.

§ 9.1.3 Defining the scope of the research

§ 9.1.3.1 Primary research objective + outcomes

Thus, the primary research objective of this chapter is to explore the potential of the design of constructed environments to promote ecological behavior. This chapter addresses this research objective by identifying and evaluating the effectiveness of a myriad of design strategies and guidelines that promote ecological behavior. These findings can aid design teams in developing constructed environments that promote diverse ecological behaviors.

§ 9.1.3.2 Research boundary limits

Relative effectiveness of individual ecological behavior design strategies

The potential effects of the various ecological behavior design strategies and solutions that are explored throughout this chapter on the ecological integrity of local ecosystems are discussed within their respective sections. However, it is important to note that further research is necessary to evaluate the relative effectiveness of various ecological behavior design strategies and solutions, as discussed in more detail in Sections 9.2.7 and 9.6.

Scale

Ecological behavior can be addressed from a myriad of scales and perspectives, from the global and national levels to the scale of the individual. This chapter is focused on the potential of the design of individual constructed environments, such as individual buildings and landscapes, to promote ecological behavior among the inhabitants. The value of focusing on this scale is discussed in Section 9.2 and Chapter 8.

Context

Furthermore, as discussed in Chapter 8, this chapter is focused on exploring the design potential of constructed environments to promote ecological behavior within the context of urban core ecosystems. Urban core ecosystems, albeit a challenging context, present unique opportunities to design for ecological behavior. Moreover, the urban core ecosystem context provides the potential for individual design for ecological behavior solutions to directly interact with, and affect the behavior of, large quantities of people during their daily life routines, as well as during their leisure and business activities. In other words, design for ecological behavior within urban core ecosystems can be more effective and efficient than in less concentrated constructed ecosystems. Furthermore, it is important to note that in many cases, the strategies and solutions discussed within this chapter are also applicable to other contexts.

§ 9.1.3.3 Sub-research objectives

Effective methods to promote ecological behavior at the scale of individual constructed environments can be addressed through both the design of their spatial qualities, as well as the activities that they provide, as illustrated in Figure 9.1. Thus, design strategies that have been found in existing literature to be effective in promoting ecological behavior, as well as innovative design strategies that were developed based on the evidence of existing literature, are organized and discussed within the context of these two general design categories: the spatial qualities of constructed environments, as described in Sections 9.3 and 9.4, and the activities conducted within constructed environments, as described in Section 9.5. It is important to consider that although the various design strategies that are discussed within this chapter are organized within these two general design categories, some design strategies, such as eliminating barriers and providing resources, are applicable to both design categories.

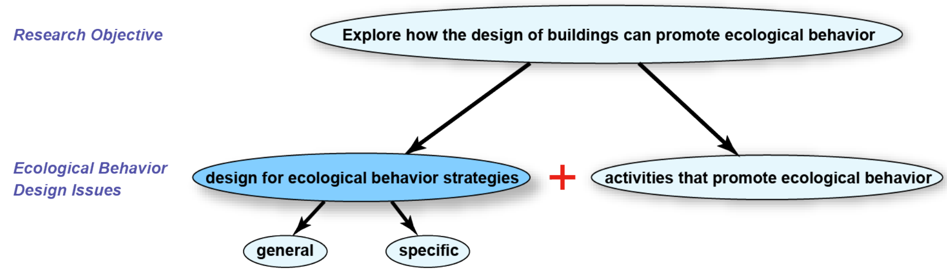

FIGURE 9.1 Constructing ecological behavior chapter overview

§ 9.2 Identifying general design for ecological behavior strategies

§ 9.2.1 Defining the potential value of designing urban habitats to promote ecological behavior

The integration of natural environments within constructed ecosystems inherently provides a range of benefits for the local community. For instance, interactions with natural environments have been found to improve physical and mental health and well-being, reduce stress, and improve individual and community rates of socialization.[33, 49, 199, 233] In terms of direct economic benefits, the value of properties near natural environments have been found to increase.[475] There are a myriad of additional economic, social, and ecological benefits to integrating natural environments within constructed ecosystems, some of which are discussed in Sections 9.3.4, 9.3.6, and 9.4.

Furthermore, urban habitats can inherently benefit from being in close proximity to human resources, infrastructure, and inhabitation in a plethora of ways, in terms of promoting ecological behavior and reducing the ecosystem service footprint of the local community. For instance, as discussed in Section 9.1.1, since the majority of people live in or near urban areas, and most people's experience of nature occurs in urban areas, a habitat patch within an urban area will be experienced by more people, as well as more frequently, than a habitat patch which is situated outside of urban areas.[391] Thus, habitat patches within urban areas have greater potential to promote ecological awareness and ecological behavior, in terms of the quantity of interactions people have with natural environments and processes. Moreover, multiple habitat patches that are distributed throughout a constructed ecosystem have a greater potential to improve ecological behavior than an individual habitat patch, by increasing the potential frequency and probability of interaction with nature by a larger quantity of people. Nevertheless, it is necessary to assess the relative importance of the quantity of interactions with nature compared to the quality of interactions with nature, as well as the quality of the individual habitat patches, in regards to determining the effectiveness of these patches in promoting ecological behavior via high quality, interactive experiences. Design strategies that may effectively address these issues are discussed in the following sections of this chapter. Moreover, effective ecosystem service footprint design strategies are discussed in Chapter 10.

In addition, the proximity of municipal infrastructure systems to natural habitats that are situated within urban areas provides the opportunity for these habitats to generate a range of ecosystem functions efficiently and effectively, without disturbing existing, more 'pristine' natural environments. For instance, a constructed wetland within an urban park can filter nitrogen and phosphorous from the wastewater of the local neighborhood before the wastewater is sent to the sewer system. Moreover, the close proximity of this wastewater infrastructure system to local urban communities provides opportunities to demonstrate the diverse values of natural environments, the causes and effects of individual and community resource consumption, ecological solutions to mitigating resource consumption and their negative consequences, as well as the mutual benefits that are gained by integrating natural environments and processes with constructed environments and processes. For instance, natural habitats can be incorporated into the infrastructure processes of building and municipal infrastructure systems. For example, in the town of Kolding, Denmark, the wastewater and stormwater of a low income residential block is treated on site via a vegetation integrated treatment plant that eliminates the discharge of any water from the block. The treatment plant includes a glass pyramid that allows horticulturalists to grow approximately 15,000 commercial plants at any given time, as well as reed beds that function both as neighborhood garden space and part of the filtration process.[222] This infrastructure system provides vital municipal infrastructure processes that eliminate the adverse effects of the neighborhood's sewage, reduce their rates of water consumption, provides economic opportunities for the local community, and provides a natural habitat patch for the local human and ecological community. In addition, natural habitats can be incorporated into existing infrastructure spaces, such as under highways and within the sites of waste management plants, in ways that foster these types of symbiotic interrelationships. For instance, constructed wetlands adjacent to highways can be implemented to filter stormwater runoff, as well as to provide stormwater and wastewater infiltration. Effective design for ecosystem functions such as these are discussed in more detail in Chapter 10.

Moreover, the proximity of urban habitat patches to the daily activities of the local community, in regards to all age groups, allows these spaces to facilitate a diverse range of activities that promote ecological behavior, including education, attention restoration, long term exposure to nature, recreational activities, and local species observation and interaction.[199, 320, 411] For example, the relative close proximity of these natural spaces to school environments, in comparison to nature reserves, provides schools with opportunities to make more frequent trips to natural environments. In doing so, more frequent experiences in natural environments can be effective in increasing the ecological behavior of individuals, as discussed in more detail in Section 9.2.3.[16, 57] The potential of various activities to promote ecological behavior is further discussed in Section 9.5.

Thus, the design of constructed environments within urban areas to promote ecological behavior has the potential to provide a diverse range of benefits to the local community, as well as to the local and global natural ecosystems.

§ 9.2.2 Designing experiences for effectively generating diverse ecological behaviors

Individuals and communities are constantly engaging in a diverse range of human behaviors and activities that directly and indirectly impact local and global ecosystems.[319] Furthermore, it is important to note that an individual's overall environmental impact is the result of the cumulative consequences of their individual behaviors. Thus, it is important to comprehensively evaluate the impacts of the specific behaviors and activities of individuals and communities on local and global ecosystems. However, a comprehensive review of the effectiveness of every type of behavior that affects local and global ecosystems is quite broad, and outside the scope of this chapter. In recognition of the broad scope of this issue, Kaiser (2004), among others, analyzed the effectiveness of the categorization of various conservation behaviors.[236] These types of categorization strategies can help determine the effectiveness of both general and specific design for ecological behavior strategies.

The design of constructed environments to promote ecological behavior can thus be considered from an overall behavior perspective, as well as from the perspectives of individual behaviors and categories of behaviors. The following subsections discuss potential issues that should be considered when designing for ecological behavior from these various design perspectives.

§ 9.2.2.1 Design for positive spillover effects

To this end, researchers have found evidence that various individual behaviors are inherently interrelated and influence each other.[236, 435, 436, 448, 477] For instance, Thogersen (1999) found evidence that a spillover effect in people's behavior is sometimes developed, whereby an individual behavior conducted in an ecologically friendly manner inherently results in the individual conducting other behaviors in an ecologically friendly manner.[435] For instance, direct feedback of individual appliance energy consumption can affect a household's energy consumption rate of the specific appliance, as well as other appliances.[448, 477]

§ 9.2.2.2 Design to minimize negative spillover effects

Moreover, there is evidence that negative spillover effects can be developed as well. A negative spillover effect occurs when an individual conducts an ecological behavior, and it has a negative impact on the individual's perceived obligation to perform other ecological behaviors.[435] Although a number of explanations for these types of negative effects have been proposed, existing research suggests that the most likely explanation is that while some behaviors are easy to perform in an ecological manner, others are perceived as too costly, difficult, or inconvenient to conduct in an ecological manner. Thus, individuals may perform the more easy tasks in an ecological manner as an excuse to not perform the more difficult tasks. In addition, conducting easy tasks may cause some individuals to believe further ecological behaviors are unnecessary.[319, 435]

Existing literature suggests that these potential negative spillover effects can be resolved through various design strategies. For instance, extant research from a number of different goal oriented behavior theories, such as the Goal Oriented Theory and Theory of Planned Behavior discussed in Section 9.4.1, suggests that an effective solution to mitigate negative spillover effects is to make the performance of a behavior in an ecological manner be perceived to be more beneficial and less costly than performing the task in a non-ecological manner, or at least reduce the perceived gap.[31, 236, 297, 319, 419] Potentially effective design strategies to address negative spillover effects are discussed in more detail in Section 9.4.

§ 9.2.2.3 Design for multiple spillover effects in diverse behavior categories

Furthermore, extant research in relation to goal oriented behavior theories indicates that designs should provide numerous opportunities for individuals to engage in ecological behavior, in order to increase the individual's frequency of conducting ecological behavior. Moreover, repeatedly performing ecological behaviors may make an ecologically oriented attitude more accessible in one's memory, thereby making other mental constructs that an individual strongly associates with this attitude more accessible, through an unconscious spreading activation process.[144] Over time, frequently conducting ecological behaviors may help re-orient an individual's self-identity to be more ecologically focused, which would motivate them to perform ecological behaviors.[297, 319] This effect is discussed more in Section 9.4.1.

However, existing literature indicates that spillover effects may mostly occur between behaviors that are within the same behavior category. Moreover, an individual's overall ecological behavior does not seem to determine an individual's behavior, in regards to specific ecological behaviors. In other words, ecological behavior, in regards to a specific task, does not necessitate ecological behavior in other tasks. Furthermore, an individual's overall ecological behavior cannot be determined by evaluating a specific behavior or behavior category.[167, 236, 436]

Since some ecological behaviors produce positive spillover effects in regards to other behaviors within the same behavior category, design for multiple behaviors within the same behavior category may be a more effective design strategy than designing for multiple opportunities to conduct the same ecological behavior. For instance, this strategy may result in individuals modifying their behavior in regards to multiple or all of their individual behaviors that are associated with an individual behavior category. Moreover, design for multiple behaviors within the same behavior category may in some cases also positively affect some of the individual's behaviors that are associated with other behavior categories.[319] For example, a study by Thogersen (2003) found a few related behaviors in different behavior categories were affected by spillover effects slowly over time. Interestingly, a majority of studied behaviors were found to be conducted frequently, and in a relatively consistent context, which suggests that these behaviors became habitual over time.[436] Thus, the design of constructed environments should consider how to promote individuals to change negative ecological habits and form positive ecological habits. The development and design for habits is discussed in more detail in Section 9.4.2.

§ 9.2.2.4 Design for multiple + specific behaviors

Therefore, the results of extant research indicate that the design of constructed environments should consider promoting multiple ecological behaviors, because addressing individual ecological behaviors will not effectively improve an individual's overall behavior. In addition, design teams should consider and investigate the inherent interrelationships of various behaviors and behavior categories, as well as provide opportunities to conduct ecological behaviors frequently. Furthermore, existing literature indicates that it is important to address individual ecological behaviors.

These goals can be achieved through a number of ecological behavior design strategies. To this end, the subsequent sections of this chapter discuss general design strategies that promote individual and community ecological behaviors. Furthermore, the potential for the design of constructed environments to promote specific ecological behaviors is discussed in more detail in Section 9.4. Moreover, future research should explore the potential of various design strategies, at the building, site, and individual space scale, to effectively promote positive spillover effects, mitigate negative spillover effects, as well as promote individual and multiple ecological behaviors.

§ 9.2.3 Design for frequent, positive nature experiences

The effects of singular experiences in natural environments on people's ecological behavior have been found to decline over time.[421] On the other hand, extant research indicates that frequent, positive interactions with natural environments and processes, such as in one's daily lifestyle, are particularly effective at promoting ecological behavior.[86, 145, 235, 237, 329, 430, 487] For instance, there is evidence that having repeated, positive experiences in nature while conducting various behaviors and activities may generate positive habits.[419] This concept is discussed further in Section 9.4.2. In addition, existing research focused on goal oriented behavior theories indicates that people's behaviors are partially influenced by the pleasure and benefits they derive from the behavior, as well as the frequency with which they conduct the behavior. These effects are discussed more in detail in Section 9.2.2 and 9.4.1. Furthermore, the frequency of an individual's experience with nature has been found in several studies to be one of the most effective methods to develop an emotional connection between an individual and nature, which has also been found to generate various ecological behaviors.[86, 237] This concept is discussed in more detail in Section 9.3.1. To this end, there is also evidence that people's preference for specific environments may increase directly with the number of previous positive experiences they have had in a specific environment, which is discussed in greater detail in Section 9.2.6 and Section 9.3.7.[86, 95, 191] Thus, in terms of promoting ecological behavior, it is evident that it is important for individuals to have repeated, positive experiences in natural environments.

In addition, the duration of experiences in nature may influence their effects on people. A meta-analysis of ten UK studies, which in total comprised 1252 samples, found that people's mental health increasingly improved with the length of time they spent exercising in nature. However, short periods of exercise were found to be effective, and longer periods of exercise showed increasing, but diminishing rates, of positive effects.[33] In contrast, Collado (2013) found the amount of time spent in nature during an ecological education program did not have an impact on the ecological behavior of the participants.[95] Hence, the effects of the duration of conducting various activities on the ecological behavior of the participants, as well as their physiological and psychological well-being, merit further research.

§ 9.2.4 Building potential to generate ecological behavior

Unfortunately, the fast pace of modern society can cause people to feel that they don't have time to visit natural environments.[320] Indeed, Americans and Europeans typically spend 80 - 90% or more of their time indoors.[447] Thus, within these societies, an effective strategy to integrate natural environments and processes into the everyday lives of individuals and communities is to incorporate natural environments and ecological functions into building environments. Indeed, the design of building environments and systems afford a diverse range of opportunities to provide positive experiences with natural ecosystem functions and environments. At the same time, the design of building environments and systems provides numerous opportunities to interactively make people aware of the benefits of natural ecosystem functions and environments, as well as the inherent interrelationships between urban communities and local and global ecosystems. To this end, existing research has found that the integration of natural environments and processes into built environments can also benefit the performance of buildings and building systems, as discussed in Chapter 4.[218, 292]

§ 9.2.5 Design for diverse, numerous, valuable constructed environments to generate ecological behavior

However, there is relatively little existing research on the specific qualities of natural environments and processes, as well as general spatial qualities and activities, that are effective at promoting ecological behavior. For example, Freeman (2012) found that people prefer diverse plant species in their gardens, but the effectiveness of species rich gardens compared to gardens with low species richness on occupants' ecological behavior was not evaluated.[159] In addition, it is important to consider the possibility that the effectiveness of various spatial qualities may differ based on the types of activities occupants engage.

Nevertheless, by providing natural environments that are conducive for conducting a range of activities, the frequency of people's interactions and experiences with nature can be increased. In turn, frequent positive interactions with nature can promote ecological behavior, as discussed in Section 9.2.3. Furthermore, existing research indicates that people can benefit psychologically and physiologically from conducting a variety of activities in nature, such as various social and work activities, as discussed in Section 9.4, as well as Chapters 4-7. Moreover, people who experience benefits from nature have been found to be motivated to conduct ecological behavior.[95, 113] Thus, the provision of spatial qualities that people prefer, as well as spatial qualities that provide benefits to people, for a range of activities, may effectively promote ecological behavior.

§ 9.2.6 Design for recursive nature-experience feedback loops

The provision of diverse, numerous natural environments that generate positive, beneficial experiences for a variety of activities can potentially generate a self-reinforcing and recursive positive feedback loop. This effect can be referred to as a *recursive nature-experience feedback loop*. For instance, the design of natural environments that provide psychological and physiological benefits to occupants may attract more people to interact with these environments, as well as promote repeated experiences of these spaces by individuals. In some cases, the provision of natural environments may also provide access to these types of environments, and inherent benefits, to communities that did not previously have access to these resources. These effects would inherently support the development of positive ecological behavior habits and social norms, which are discussed in Sections 9.4.2 and 9.4.3.

Moreover, if people perceive these environments to be valuable for conducting a range of activities, it would increase the perceived value of these spaces, and thereby promote the development of additional natural environments, for a range of activities. Increased development, in turn, would provide greater opportunities for the local community to experience natural environments and reap the benefits of these interactions, as well as the inherent and designed benefits and services that natural environments can provide. Since positive experiences in natural environments also increase ecological behavior, including the restoration and preservation of natural environments, the development of additional natural environments would be promoted in multiple ways. In turn, the increasing development of natural environments within urban areas would also promote greater ecological behavior among more people, and increase the quantity of benefits for the local community, thereby potentially generating a magnification effect, which is described in Section 9.3.2. The development of this positive feedback loop would also contribute to reversing the 'Shifting Baseline Syndrome' that affects human communities within urban areas that are negatively affecting the ecological integrity of local natural ecosystems, as discussed in Section 9.3.3.

§ 9.2.6.1 Potential effects of recursive nature-experience feedback loops on urban sprawl

It is interesting to note that since natural environments have been found to be optimal environments for a diverse range of activities, the development of natural environments has the potential to reduce urban sprawl and urban development costs by providing multifunctional spaces that would otherwise require the development of separate, lower performing constructed environments for each individual activity. In addition, the provision of higher quality environments within urban core ecosystems that promote a range of activities may increase people's valuation and preference for urban core ecosystems, thereby encouraging people to live in urban core ecosystems, rather than suburban and rural ecosystems.[320] Thus, the development of natural environments for human activities can be, in some cases, a more efficient and effective development strategy than existing development practices. Furthermore, the development of an increased valuation of constructed and natural environments by communities can potentially promote the preservation of local natural habitats and the reduction of urban sprawl in diverse ways.

§ 9.2.6.2 Exploring the application potential of recursive nature-experience feedback loops

These findings, among others, suggest that conducting any activity in a natural environment that benefits from being conducted in a natural environment can help promote ecological behavior. This is because it would increase the occupants' valuation of, and attachment to, natural environments, as well as increase their preference for conducting the activity in a natural environment. As a result, the occupants' frequency of inhabiting natural environments would increase, thereby further promoting ecological behavior. Hence, these findings suggest that an effective general design strategy to promote ecological behavior would be to integrate natural environments and processes into the design of spaces for any activities that people benefit from, and prefer conducting in, natural environments. Similarly, an effective design strategy may be to incorporate natural environments into as many spaces as possible, so long as the natural environments benefit the activity and experience of the space. Therefore, the provision of numerous, easily accessible natural environments that provide opportunities for the local community to have frequent, positive experiences in natural environments, in regards to a diverse range of activities, is an effective general design strategy for promoting ecological behavior.

§ 9.2.7 Summarizing the potential general natural environment design strategies that can promote ecological behavior

However, there is relatively little research on the effectiveness of conducting a range of activities in natural environments on directly promoting ecological behavior, beyond recreational, educational, and restorative activities. Further research into the potential of conducting a diverse range of activities in natural environments, as well as other high quality environments, to promote ecological behavior are necessary to identify and evaluate the potential benefits of integrating natural environments into previously unconsidered activities and constructed environments. To this end, it is also essential to explore and evaluate various spatial qualities that may improve the performance and experience of various activities. Moreover, Chapters 6 and 7 review a number of potential benefits that integrating natural environments into office buildings can provide.

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On the other hand, the diverse range of activities that have been found to benefit from being conducted in natural environments are too broad to comprehensively review in this chapter. Nevertheless, several activities that have been found to directly promote ecological behavior when conducted in natural environments are discussed in Section 9.5. Moreover, various spatial qualities and design strategies that have been found to promote ecological behavior, promote the occupation of natural environments, and provide physiological and psychological benefits are discussed in Section 9.3. In addition, various spatial qualities and design strategies that can promote resource consumption behavior are explored in Section 9.4.

§ 9.3 Exploring spatial qualities + design strategies that promote ecological behavior

As discussed in Sections 9.2.3 and 9.2.5, extant research indicates that the provision of high quality, beneficial natural environments that generate positive experiences and interactions will increase occupants' ecological behavior. Thus, the spatial qualities that compose constructed environments directly affect the potential of the environment to promote ecological behavior. For example, different spatial qualities are preferred, as well as beneficial, for conducting different work tasks and activities, as discussed in Chapters 6 and 7. These findings suggest that the design of a space should not simply combine all the spatial qualities that have been found to promote ecological behavior and positive experiences, but rather should critically assess and include the spatial qualities that will improve the experience of the space in regards to the activity being conducted, as well as promote ecological behavior. Therefore, the development of high quality, engaging natural spaces within urban contexts that promote ecological behavior is inherently a design problem that should be considered in the design process of constructed environments. Moreover, it is important to note that previously unconsidered design strategies may also be effective at promoting ecological behavior, and should be explored through future research projects.

Thus, the following subsections identify and evaluate a number of design strategies and types of spatial qualities and environments, some of which have not been previously considered, that existing literature indicates may successfully promote ecological behavior and positive experiences, are preferred by people for various activities, provide benefits to the occupants, and in some cases, foster an emotional connection with nature.

§ 9.3.1 Design for Emotional Affinity towards Nature (EAN)

Although people's general concern for the environment has not been found to directly influence their ecological behavior, one's measured emotional affinity towards nature (EAN) has been found to predict people's pro-environmental commitment and ecological behavior.[86, 95, 112, 237, 329] Furthermore, a number of types of experiences in nature have been found to generate a personal affinity to nature.[95, 237, 284] To this end, Kals, Schumacher, & Montada (1999) evaluated people's EAN through four performance categories: love of nature, feelings of freedom in nature, feeling of security in nature, and feelings of oneness with nature.[237] These qualities can be helpful as general guidelines for designing constructed environments that are meant to promote ecological behavior. Nevertheless, further research is necessary to determine the potential of more specific spatial qualities and environments to promote ecological behavior and EAN.

§ 9.3.2 Design for magnifying effects

Sometimes an experience or event can have an inordinately large resultant effect, which can be referred to as a *magnifying effect*. An example project is the Jardin d'Arboriculture, which was designed by Adolphe Alphand in 1868.[11] The garden was divided into two equal areas: one area was filled with local edible plants, and the other was filled with local ornamental plants. The goal of the project was to expose visitors to native plants that were becoming increasingly rare in the region, that were not yet well-known, and/or were thought to be too difficult to grow and maintain. Alphand believed that through direct sensory interaction with the plants, through the smelling and tasting of their fruits and fragrances, through seeing and feeling their vivid colors dynamically interact with veils of sunlight, gusts of wind, and meandering butterflies, the visitors would be inspired to cultivate these species in their homes, places of business, and community spaces. He believed that the local community would place a higher value on protecting, restoring, and inhabiting natural environments, through their personal interactions with nature. Alphand also developed low cost, efficient training systems for the plants, so that visitors would have examples of how to effectively and efficiently grow the plants. He did this to alleviate concerns that growing plants was too physically difficult or cost prohibitive. Although unbeknownst to Alphand at the time, these theories are supported by the ecological behavior research discussed in this chapter.

The development of these types of interrelationships in a single project can have a magnifying effect, by providing opportunities for individual experiences for a large quantity of people. From this perspective, each interaction provides a new possibility for native plants to be planted throughout the region, potentially leading to the generation of habitat patches throughout the urban area, and improving the ecological integrity of local and global ecosystems.

§ 9.3.3 Design for addressing + reversing Shifting Baseline Syndrome (SBS)

There is evidence that urban areas are increasingly undergoing an 'extinction of experience' of natural environments, as discussed in Section 9.1. Moreover, there is evidence in existing literature that this effect is generating a '*shifting baseline*' syndrome among communities, whereby frequent interaction with degraded natural environments leads people to perceive these low quality natural environments as normal. For instance, Kahn & Friedman (1995) found inner city children in Houston did not perceive an air pollution problem in their city, even though Houston had one of the worst air pollution concentrations for a city within the US.[232] Furthermore, this concept suggests that the quality of natural environments that are encountered during one's childhood becomes the baseline against which environmental degradation is measured later in life. Therefore, as natural ecosystems become more degraded from generation to generation, people's expectations regarding the quality and ecological functions of natural ecosystems diminishes, which allows further degradation.[29, 351, 356]

This trend can be reversed. For instance, if the natural environments that people commonly experience are improved rather than degraded, than people may begin to expect higher quality natural environments in their communities than are currently typically developed. There is substantial evidence within existing literature to support this theory. For instance, direct, positive, and frequent experiences with high quality natural environments, biota, and processes have been found to promote ecological behavior and valuation of nature, as discussed in Sections 9.2.3, 9.3.1, and 9.3.4. Moreover, there is evidence that individuals and communities will become more perceptive of the relatively poor quality of currently degraded natural environments by experiencing, and comprehending the value of, higher quality natural environments, via the inherent feedback effect of the comparative experiences, as discussed in Section 9.4.4.[212, 271]

Thus, if people have more stimulating, meaningful, sensuous, and personal interactions with nature, than their expectations, understanding, and valuation of the quality and ecological functions of natural environments and processes may increase. This can be achieved through a number of design strategies. For instance, it may be important to promote species richness within urban core ecosystems, in order to increase the quantity and quality of interactions communities have with local species. This is because an increase in species richness may promote the valuation of nature by fostering increased positive interactions between natural and human communities. In turn, these interactions may cause individuals to perceive nature as a positive, inherent aspect of their daily lifestyles. Furthermore, by becoming more familiar with natural environments, organisms, and processes, people may become more perceptive of degraded and low quality natural environments, and thereby be encouraged to improve these environments. These concepts are discussed in more detail in Sections 9.2.6, 9.3.4, and 9.3.10. Moreover, these types of interactive experiences may result in the development of more symbiotic interrelationships between human and natural environments and processes, leading to more sustainable lifestyles, greater demand for nature conservation and restoration efforts, and thereby, improved local and global natural ecosystems. The potential benefits of this *recursive nature-experience feedback loop* are discussed in more detail in Section 9.2.6. Furthermore, by improving the ecological integrity of local ecosystems, the local community would gain additional valuable ecosystem functions, which is discussed in more detail in Chapter 10. However, it is important to note that within some contexts, increasing species richness within urban core ecosystems can be detrimental to the local natural ecosystems and species populations, such as by generating ecological traps and increasing competition for local resources between species, as discussed in Chapter 11.

§ 9.3.4 Design for direct, personal experiences

Existing research indicates that direct experiences with natural environments, such as gardening, are more beneficial, and have a greater effect on people's ecological behavior, than indirect experiences, such as walking by a garden or living wall on the way to one's workplace.[126, 159, 233, 472] For instance, Weinstein (2009) found that participants that immersed themselves more in natural environments exhibited more social behaviors.[472] Moreover, people who establish direct, personal connections with nature have been found to exhibit ecological behavior, as well as be more highly motivated to protect natural environments. This is partly due to the development of an emotional affinity to nature (EAN), which has been found to be developed through direct, personal interactions with nature. EAN is discussed in more detail in Section 9.3.1.[85, 97]

To this end, direct experiences typically have a greater potential to provide opportunities for personalization and emotional attachment to nature, whether it's through an occupant cultivating their own plant, or having a favorite spot in an urban forest.[159] In addition, direct, personal experiences with natural environments have been found to provide more rounded, complex, engrossing, and stimulating interactions than indirect experiences, as well as provide more mental energy and restoration, and be better able to stimulate and captivate people's attention.[126, 159, 233] For instance, direct interactions with natural environments also provide opportunities to interact with wildlife, which can promote personal interactions with natural environments, provide a diverse range of benefits, as well as promote ecological behavior, as discussed in Section 9.3.14.

TOC

§ 9.3.5 Effects of degree of naturalness of environments on occupants

§ 9.3.5.1 Relative effectiveness of different types of natural environments

Existing literature indicates that diverse and stimulating natural environments are more effective at promoting ecological behavior than typical homogenous, non-stimulating environments.[86, 95, 159, 163, 320, 475] Furthermore, extant research has found that people's valuation and preference for natural environments, as well as the physiological and psychological benefits they acquire from interacting with natural environments, increases as the perceived quality of the environment increases. For example, the benefits people attain from natural ecosystems have been found to increase as the species richness, physical size, degree of naturalness, and quantity of accessible, diverse habitats within natural ecosystems increases.[121, 163, 239, 276, 288, 475, 487] For instance, in terms of people's perception of species richness, Fuller (2007) found that parks with greater plant diversity were found to provide more psychological benefits to occupants than more monoculture parks. Interestingly, the diversity of static species, such as plants, were noticed and evaluated more than the richness of active species, which suggests that different spatial qualities and components of natural environments have different effects on people.[163] Although the diversity of plant species may be more noticeable to visitors, Dick & Hendee (1986) found that the quantity of animals, as well as the diversity of animals, was positively correlated with attracting people's attention. The value of wildlife in promoting ecological behavior is discussed in more detail in Section 9.3.14. Furthermore, White (2010) studied the perceived restorativeness of various built and natural environments, as well as participant's preference for the environments. Interestingly, the participants' general preference for an environment increased in line with the overall quantity of natural elements in the environment.[475] Kaplan (2007) found more less maintained, prairie type landscapes were preferred over typical mowed landscapes by office workers.[239] In another study, the diversity of types of natural areas, as well as plant diversity and diversity of different types of bright colors, were preferred for the design of meadows by visitors of a botanical garden in Switzerland.[276] These findings, among others, indicate that robust, diverse natural environments are more psychologically beneficial, preferred, engaging, and effective at promoting ecological behavior than more homogenous, less stimulating environments, such as common extensive lawnscapes.

§ 9.3.5.2 Relative effectiveness of constructed environments

However, this does not mean that urban parks are necessarily less valuable or effective than natural ecosystems. On the contrary, in terms of their restoration potential, there is evidence that urban parks and green spaces can be just as effective as natural ecosystems in rural areas.[474] Furthermore, although existing research indicates that natural environments are more restorative than constructed environments, these research projects have not typically evaluated the potential benefits of constructed environments that are designed to be restorative. Nevertheless, there is evidence that constructed environments can be designed to be more restorative than typical constructed environments, and potentially as restorative as natural environments. For instance, Karmanov and Hamel (2008) found that Dutch constructed environments that included pleasant water areas were as restorative to their participants as a rural woodland.[243] These findings indicate that the value and benefits of constructed environments depends on their design, and the way environments are perceived by their occupants.

§ 9.3.5.3 Potential effectiveness of hybrid environments

Furthermore, these findings suggest that the design of constructed environments can improve their ecological and psychological value and benefits, as well as the experience of the occupants. For example, there is evidence that the design and development of innovative hybrid environments, which are environments that combine natural and human-made features, may generate significant benefits. Diverse civilizations have developed hybrid environments, such as traditional Chinese and Japanese courtyard gardens and the Victorian greenhouses in Europe. However, to the extent of the author's knowledge, the potential ecological and psychological benefits of these types of environments have not yet been rigorously scientifically evaluated. Nevertheless, research from a variety of disciplines, such as restorative environments and EAN, have identified several general spatial qualities that can be effective, and are discussed in this chapter in their respective sections. The results of this research review indicate that it would be beneficial to further investigate the potential benefits and effectiveness of integrating various natural environments, features, and processes into constructed ecosystems.

§ 9.3.5.4 Identifying future research topics for determining the effects of different types of natural environments and stimuli

To this end, further research into the effects, interrelationships, and benefits of the degree of naturalness and perceived quality of various environments, in terms of promoting ecological behavior, may provide insight into high performing design solutions. Further research into the respective value of varying levels and types of direct and indirect experiences may also provide deeper insights. For instance, the value of one type of experience compared to another, and the influence of the quantity of experiences, requires further research. For example, Collado (2013) found direct experiences influenced children's ecological behavior, while the childrens' participation in an environmental education program did not have an effect on their ecological behavior.[95] However, other studies have found conflicting results, which makes the relative effectiveness of direct experiences of nature, compared to learning about nature, on one's ecological behavior still relatively unclear, as discussed in greater detail in Section 9.5.2.

Further research is also necessary to determine the effectiveness of different qualities of natural environments. For example, the effectiveness of different types of urban habitat patches on promoting ecological behavior, as well as the effect of walking in urban habitat patches compared to interactions with nature in more pristine natural environments, such as a mountain peak or seaside, has yet to be effectively evaluated. Moreover, the effects of spending different quantities of time in nature, as well as the effectiveness of interacting with different types of wildlife, also remain unclear. For example, interactions with animals have been found to increase learning opportunities and physiological health for people of all ages, which may indicate animals provide more direct and effective interaction opportunities.[233] However, in a study on the perceived value of various garden qualities by Freeman (2012), people identified the presence of plants more than animals as the most important feature of a garden.[159] Although the various sections of this chapter discuss the results of existing research on these diverse topics, there is currently scant existing literature on the types of spatial qualities and physical environments that people will benefit from, in terms of ecological behavior, as well as in regards to other performance parameters. This makes it difficult to evaluate the relative effectiveness of various design solutions. Nevertheless, the discussions within this chapter provide a number of insights that can be used as design guidelines. It is also important to note that the effects and benefits of various environments vary by activity, as discussed in greater detail in Section 9.5.

§ 9.3.6 Design for restoration

Personal interactions with restorative environments have been found to promote a number of ecological behaviors.[21, 42] Furthermore, experiences within restorative environments have been found to relax people, reduce their stress, restore their direct attention capabilities, and increase their preference for a space, among other benefits. [49, 199, 241, 431] Thus, research in the field of restorative environments may help identify and evaluate the effectiveness of several spatial qualities that promote ecological awareness and behavior. Furthermore, key concepts from this research domain may provide useful design guidelines for designing spaces in buildings that are effectively utilized by the occupants, and develop more direct, personal interactions between building occupants and natural environments.

§ 9.3.6.1 Defining ART

According to Attention Restoration Theory (ART), an individual's direct attention is depleted by engaging in direct attention activities, which are activities that require prolonged mental efforts. This includes effort to remain focused, despite frequently occurring distractions that are common in daily life. For instance, intensive work tasks, such as problem solving and brainstorming, require direct attention. Conversely, restorative environments are environments that restore people's direct attention capabilities, by engaging people's attention through experiences that do not require effort to sustain their attention.

Existing research has explored and evaluated how to develop and identify effective restorative environments, as well as how to determine the potential benefits of interacting with restorative environments. For instance, natural environments have been found to perform well as restorative environments, partly because attention to natural stimuli has been found to be effortless and restorative.[49, 199, 241] Furthermore, a range of activities, spatial qualities, and environments have been found to promote restoration. For example, engaging in various types of exercise in natural and constructed environments has been found to generate restoration, although the various spatial qualities that contribute to restoration have not been comprehensively evaluated in these cases.[474] In addition, although much of the existing research on the effectiveness of natural and constructed environments performing as restorative environments has compared the two as general environment typologies, Ivarsson (2008), among others, found that different types of similar environments, such as different gardens, were perceived as providing different levels of restoration. This was partly due to the fact that environments that are generally similar still tend to have different individual spatial qualities. These more subtle differences in spatial qualities were perceived by the inhabitants, and they affected the perceived benefits of the environments.[431] The study that is discussed in Chapter 7 found similar results for various types of vegetated environments.

These results indicate that there are a diverse array of spatial qualities and environments that may promote restoration that have yet to be evaluated, and that different spatial qualities and environments provide different levels of restoration. Hence, further research into the restorative performance of a more diverse range of specific environments and spatial qualities is necessary. Nevertheless, extant research has found that engrossing, direct, personal, easy to engage stimuli and experiences attain and sustain people's attention in a restorative manner. Moreover, there are four general design qualities that have been found to be effective in evaluating the performance of environments in terms of their ability to function as restorative environments: *Being away*, *Fascination*, *Extent*, and *Compatibility*.[241] A brief overview of these qualities is presented below. Mangone and Teuffel (2011) provide a more detailed overview of the design potential of restorative environments.[296]

§ 9.3.6.2 Defining restorative spatial qualities

A space that causes inhabitants to feel like they are *being away* from distractions and routines that require sustained directed attention has been found to be restorative. In general, there are two types of *fascination stimuli*: soft and hard. Attention to *soft fascination* stimuli is effortless and does not require directed or involuntary attention, such as natural stimuli. Hard fascination stimuli are events and objects that require significant involuntary attention, such as watching a soccer game or a movie, or playing video games.[49]

A restorative environment must have *extent*, it must be coherent and rich enough in stimuli to sufficiently engage one's senses in a manner that allows for real or imagined exploration. Relatively small areas can provide a sense of extent. Paths can be designed so that small areas seem much larger, such as in Chinese and Japanese courtyard gardens, as illustrated in Figure 9.2. In addition, miniaturization, such as when occupying a cave, generates a feeling of inhabiting a different world. The environment must also be *compatible* with what people want to do, must do, and can do in the environment, and allow people to perform their desired activities effortlessly.[241]

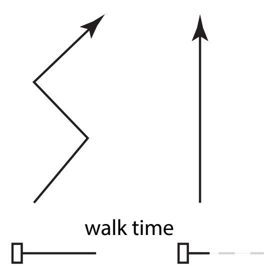

FIGURE 9.2 Walking path designed for expediency compared to prolonging experience of space

§ 9.3.7 Design for ecosystem type preference

§ 9.3.7.1 Potential savannah preference

A number of evolutionary and environmental psychology theories have been developed in an attempt to identify the types of ecosystems that people prefer to inhabit. For example, the arguably most popularly cited theory in mainstream media is the savannah preference theory, which postulates that since humans evolved for millions of years in savannahs, and learned from experience over time that open, flat spaces are relatively secure to view incoming threats, people prefer savannahs.[30] However, the results of existing studies do not support this theory.[30, 191, 192, 200, 207, 283, 484] For example, based on the results of their survey, Balling & Falk (1982) proposed an innate preference theory. This theory suggests that people have an innate preference for savannah-like settings at birth, and develop preferences for other landscapes over time based on their interactions with different natural environments.[30] However, several researchers have pointed out that the results of this study did not support their theory. For example, Balling & Falk (1982) used savannah images that were comprised of lush green parks that are typical of urban North American parks that children play in. Thus, these images were not representative of African savannahs.[200, 283]

§ 9.3.7.2 Potential forest preference

Several other evolution based environment preference theories have been proposed and evaluated. For example, Han (2007) tested the environmental preference of newly arrived students at Texas A+M University through a series of image based surveys. The surveys included samples from desert, alpine tundra, grassland, coniferous forest, deciduous forest, and tropical forest biomes. The alpine tundra and coniferous forest biomes were the most preferred in this study. Grassland savannah was one of the least preferred biomes. Han (2007) concluded that the results of these surveys support a forest evolutionary hypothesis, which proposes that human evolution took place in closed, forested settings, and therefore dense forest environments are preferred by people.[192] However, the results of the surveys did not substantially support this conclusion. For example, the participants were found to have a considerable preference for alpine tundra biomes, which does not agree with the forest evolutionary hypothesis. Similarly, the finding that deciduous forests were not more preferred than the other less dense forest types, such as the coniferous and alpine forest types, also does not support the forest evolutionary hypothesis. However, it is important to consider that the participants' preferences for alpine tundra and coniferous forest types may have been due to the participants' familiarity with these environments in their hometowns. Unfortunately, the original location of the students was not measured, which makes it impossible to evaluate the results in regards to the familiarity theory, which will be discussed in the following subsections. In addition, the selective manner in which Han (2007) presents the results of previous studies suggests a possible researcher bias.

§ 9.3.7.3 Potential preference for familiar ecosystem types

The familiarity theory proposes that people prefer environments that they are accustomed to through personal experience. A review of existing literature indicates that the familiarity theory is currently the theory that is most supported by the results of existing research.[191, 200, 207, 283, 484] For example, Herzog (2000) evaluated the relative preference of American students and Australian residents for different types of Australian landscapes. In support of the familiarity theory, Australians liked the Australian landscapes more than the Americans, and the Australian Aboriginals preferred the Australian landscape more than typical Australians. Similarly, Lyons (1983) evaluated people's preference for a diverse range of ecosystem types, including tropical rain forest, deciduous forest, northern coniferous forest, savannah, and desert.[283] The results strongly supported the familiarity theory, and did not support the innate preference theory. The participants' greatest biome preference was for the biome that was most familiar to them. In addition, desert dwellers had a higher preference for the drier and open savannah and desert landscapes than other participants. This finding is particularly interesting, since deserts and swamps were generally not preferred by the participants of the previously discussed studies.

Nevertheless, preference for deserts and swamps has been found to increase when residents in close proximity to these environments are evaluated. For example, several studies of residents in desert environments have found that deserts are rated as preferable by local residents, although not as preferable as turf landscapes. Yabiku (2008) argues that this preference may be because the residents that participated in the study were accustomed to turf grass environments, which would support the familiarity theory. To this end, Spinti (2004) found that participants that lived longer in desert towns with turf landscapes had a greater preference for turf landscapes. Nevertheless, this finding could also indicate that more lush environments are generally preferred in comparison to more arid landscapes, or the cooling function of turfgrass may be a factor.[416] In terms of swamps, Hammitt (1980) evaluated the swamp type preference of 400 onsite visitors of a national forest swamp area in West Virginia.[191] The results indicated that the participants preferred the swamp types that were most familiar to them, which in this case was a swamp forest type, and the least preferred was the more open swamp mat type.

§ 9.3.7.4 Potential preference for familiar water ecosystems

Water is another feature that is commonly reported as being highly preferred. For example, Herzog (2000) found that river landscapes were preferred the most among a range of Australian natural landscapes.[208] A study of the physiological effects of various constructed and natural environments on Swedish residents by Ulrich (1981) found that natural environments with water had a slightly more positive influence on the emotional states than natural environments without water.[450] However, preference for the presence of water has also been found to vary in studies, in accordance with the familiarity theory. For instance, Jones (1976) found that water bodies were the third most preferred landscape by local Rocky Mountain citizens, after mountains and forests.[230] Mosley (1989) found that a sample of New Zealanders perceived water as the fifth most important spatial quality, after forests and alpine qualities such as snow and ice, among other factors. Hartmann (2010) found that residents of a mountainous Spanish region responded to ads depicting familiar landscapes with clear water and lush green vegetation with the most favorable emotional responses, while unfamiliar water environments, such as tropical beaches, were not preferred. In addition, a study conducted in Plymouth, UK by White (2010) found that while water environments were more preferred than forest environments, environments where water and vegetation were mixed together were the most preferred.[475] Herzog (1985) evaluated the relative preference of 259 University of North Carolina students of different types of water environments, including mountain waterscapes, swamps, rivers, lakes, and ponds, and large bodies of water. The mountain waterscapes were the most preferred, while swamps were the least preferred. The results of this study were found to support the familiarity theory.[207] Taken together, these findings indicate that visitor's preference for water in natural environments is influenced by the types of environments that are most familiar to them, the presence of water features is in general beneficial, and that water environments are not overall more preferred than other natural environments. These conclusions are supported by the findings of White (2013), which found that woodlands, forest and hills, moorland, mountains, and coastal environments were approximately as restorative as each other, as reported by 4255 respondents in England.

§ 9.3.7.5 Ecosystem type preference conclusions + design guidelines

Thus, existing literature indicates that natural environments should be designed for interactions with native, local environments. This development method would also support ecosystem functions and the biodiversity of local ecosystems, by providing additional habitat patches for a range of species.

To this end, Hammitt (1980) proposed a method to evaluate people's environmental type preference, and recommended their preference should be evaluated when designing an environment, in order to develop solutions that provide the most benefits to the local community. Furthermore, frequent interactions with local natural environments may increase people's preference for, and value of, local natural ecosystems, as discussed in Section 9.2.3, as well as in the next section.

§ 9.3.8 Design for local nature experiences

In order to promote ecological behavior, existing literature indicates that it is important to provide easily accessible, local natural environments. For instance, since frequent, positive interactions with specific environments and stimuli have been found to increase people's valuation of, and preference for, these environments and stimuli, as discussed in Sections 9.2.3, 9.2.6, and 9.3.4, the results of existing literature suggest that providing opportunities for having personal interactions with local natural environments will promote local communities to preserve and restore local natural ecosystems. Over time, this may lead to greater conservation and restoration of local natural environments, since communities' valuation and preference for local natural environments may reduce the likelihood that they are developed into built environments. These effects could also potentially lead to the reduction of urban sprawl via magnifier effects of preserving, restoring, and valuing natural environments, as described in Section 9.2.5. This type of behavior is integral to sustain and improve the ecological integrity of local ecosystems, as discussed in Section 9.1, as well as Chapters 8, 10, and 11.

Furthermore, since the majority of people's experiences with nature tend to occur near their homes, it is important to provide local natural habitats in close proximity to people's homes. For example, a study of 4255 respondents in the UK found that the majority, 71%, of the participants' recreational trips were within five miles of their home.[474] In contrast, it is important to note that the lack of provision of natural environments and stimuli has been found to disconnect people from their native biological environments, thereby contributing to the 'shifting baseline' syndrome discussed in Section 9.3.3.[313]

§ 9.3.9 Design for education

Places of interaction with nature can be designed to educate occupants about natural environments and processes, as well as the communities' interrelationships with, and effects on, the local and global ecosystems. For instance, existing research projects have demonstrated that by educating a large number of people about local indigenous biodiversity, and by exposing them to local flora and fauna, their valuation of these species, species richness, and preserving biodiversity is increased. They also become more knowledgeable about their local natural environments.[313, 395, 476] Furthermore, valuation of local natural environments has been found to improve an individual's general ecological knowledge, and in some cases, promote ecological behavior, such as involvement in local conservation issues.[85, 97] Indeed, researchers have found that habitat protection may often be better achieved by compassionate and informed members of the local community than through command and control regulation, because land use decisions are typically made at the local government level.[383] Thus, by designing local natural environments that communities value, occupy, and have positive experiences within, they can be indirectly educated, as well as motivated to conduct various ecological behaviors. Therefore, communities can be educated actively, through ecological courses, signs, movies, etc., and passively, through experiences and interactions of individuals with natural environments and processes. Several types of specific active and passive education activities are further discussed in Section 9.5.2.

However, it is important to note that increasing one's ecological knowledge doesn't necessitate an increase in one's ecological behavior and actions, which is discussed in more detail in Section 9.5.2.[161] As discussed in Section 9.2.3, it is important to provide opportunities for frequent, positive experiences in nature, among other strategies, to promote ecological behavior. The design of environments to provide passive education opportunities can be integrated into this strategy. For instance, the various processes, possible interactions, and value of nature can be designed to be made apparent to people through their experiences and interactions with natural environments. The sample design strategies from the other sections of this chapter can aid in this endeavor. Furthermore, constructed environments can also be designed to educate occupants about their resource consumption, in terms of the quantities and effects of their resource consumption on the local and global ecosystems, as well as their own community. Sustainable resource consumption methods and behaviors can be demonstrated and developed as well. These design issues are discussed in more detail in Section 9.4.

§ 9.3.10 Design for sensuous experiences

Multi-sensory, stimulating environments have been found to increase people's evaluations of natural environments and buildings.[375, 475] For instance, natural noises, such as water, can increase people's environment preferences. Extant research also suggests that natural soundscapes are more restorative than typical urban or park soundscapes.[375, 474, 475] However, designers must be discriminating in their solutions, as some types of nature can be perceived negatively. For example, Ratcliffe (2013) found that bird sounds that were perceived as threatening or aggressive were not restorative. Nevertheless, bird calls that were perceived as pleasant have been found to provide a number of benefits.[16, 375] In addition, some human soundscapes can negatively affect people's restoration ability, such as mechanical sounds.[16]

Multi-sensory engaging environments have been found to provide a diverse range of benefits, in regards to a broad range of physiological and psychological performance parameters. For example, physical contact with solar radiation via daylight access has been found to improve people's vitality.[409] The odors of some trees, and other forest scents, may reduce stress and cause relaxation.[352, 442] Furthermore, extant research suggests that people's senses can be improved through greater use.[363] Hence, by designing spaces that engage the occupants' various senses more than usual, people may over time appreciate and value their experience of the space more, because they will be able to better perceive the benefits and value of the space. Furthermore, people may become more discerning of non-stimulating spaces and notice their lack of sensuous value. In turn, this increased sensual awareness may cause people to desire more stimulating spaces.

Thus, design for multi-sensory environments may, over time, make occupants more discerning and critical of the quality of the spaces they occupy, as well as provide additional or greater benefits. This could, in turn, improve their ecological behavior, by increasing people's valuation of natural environments. This would also promote the conservation and restoration of natural environments, as well as the integration of natural environments and processes into built environments, as discussed in Sections 9.2.5 and 9.2.6.

§ 9.3.11 Design for mystery

Natural environments that are perceived as mysterious have been found to promote the exploration of, and interaction with, natural environments. For example, Hammitt (1980) found that people preferred bogscapes that included a hidden element, a sense of mystery, to the environment.[191] Environments that are mysterious tend to have novel features and spatial environments that invite, and provide the opportunity for, occupants and passersby to explore an environment or space to further understand the environment, as well as search for additional sensory information.

A sense of mystery can be conveyed via engagement with a variety of people's senses, including hearing an intriguing sound or seeing an interesting animal scurry off into an unknown space.[449] Moreover, wildlife has been found to be particularly successful at promoting exploration, as discussed in greater detail in Section 9.3.14. Furthermore, imbuing a sense of mystery into the design and experience of a space may promote people who do not ordinarily interact or inhabit natural environments to begin to interact with them, similar to providing spaces that generate awe, as discussed in Section 9.3.12.

However, it is important to note that frequent interaction with specific natural environments has the potential to, over time, reduce the perceived newness, and therefore sense of mystery, of a given space. This effect is discussed in more detail in Chapter 6. In this respect, the dynamic nature of natural environments may help preserve the perceived sense of newness and mystery of a specific space, as the changing character and qualities of the space over days, seasons, and years will offer varied interactions and experiences.

§ 9.3.12 Design for awe

Existing research indicates that people experience awe when they encounter stimuli that is perceived to be vast in a manner that requires them to redefine their existing understanding of their experience or environment, in such a way that allows for them to make sense of the new, markedly different stimuli.[404] Within this definition, stimuli can convey vastness in terms of physical space, time, quantity, complexity of detail, ability, or in any other manner that challenges one's standard frame of reference and understanding in some dimension.[247]

Although there is currently a dearth of research on the types of stimuli and environments that stimulate awe, extant research has found that natural environments, particularly those that offer panoramic views, are frequently cited for eliciting awe in people's lives. Moreover, experiencing novel art and music has also been found to elicit awe.[386, 404] These results indicate that constructed environments can be designed to elicit awe, particularly when incorporating natural environments and design strategies focused on generating high quality, sensuous experiences. Furthermore, existing research that evaluated various effects of feeling awe found participants had greater life satisfaction, were less impatient, felt they had more free time available (which can promote socializing, relaxation, and spending time in nature), and preferred quality experiences to material products.[386, 487] These results indicate, among other benefits, that the design of constructed environments to elicit awe can generate positive experiences, thereby promoting ecological behavior.

Moreover, in terms of designing environments that promote awe, it is important to note that people tend to experience awe in less social environments.[404] This may be because social interactions can distract people from noticing, and interacting with, stimuli that promote awe. Regardless, as noted in the preceding paragraph, experiencing awe can also promote prosocial behavior.

Nevertheless, similar to the discussion about design for mystery in Section 9.3.11, it is important to note that repeated experiences with spaces and stimuli that stimulate a sense of awe may, over time, reduce or eliminate the ability of the space or stimuli to elicit a sense of awe from the occupant. This is because generating a sense of awe requires the occupant to comprehend novel and unusual stimuli, which over time, may not be perceived as novel, as discussed in Chapter 6.

§ 9.3.13 Design for happiness

Experiences that elicit happiness inherently promote positive experiences.[56] Therefore, natural environments that promote happiness can promote ecological behavior, as discussed in Section 9.2.3.

Although natural environments have been found to be able to elicit awe and happiness, it is important to note that existing research has found that the types of environments and activities that elicit happiness and awe are markedly different.[56, 247, 285, 386, 404] For instance, happiness is typically generated during positive social interactions and experiences, such as enjoyable experiences with friends and family.[56] On the other hand, as discussed in Section 9.3.12, people tend to experience awe in less social environments.[404] Thus, the design of natural environments will influence the types of benefits occupants gain from interacting with them.

§ 9.3.14 Design for wildlife interaction

Research suggests that the observation of wildlife promotes a personal affinity to nature, repeated personal experiences in nature, as well as ecological behavior.[93, 237, 375] In addition, there is evidence that interaction with wildlife generates a range of benefits for people. For example, Dick & Hendee (1986) found that the presence of wildlife promoted personal and group inhabitation and exploration of natural environments, even when a person or group of people were already engaged in another activity. Active wildlife was particularly effective, especially species that made pleasant noises, such as birds.[121] Interaction with wildlife was also found to increase the pleasure of people's experiences, which can contribute to improving people's overall wellbeing.[123] In addition, the number of animals and species was positively correlated with the ability of the animals to attract people's attention. However, it was determined that the more effortful a person's initial task, the more likely they were to not pay attention to the wildlife.[121] The presence of vocal wildlife has also been found to increase people's evaluation of, and preference for, an environment, as well as the potential of the space to provide restoration to the occupants.[16, 375] In addition, interactions with wildlife may improve the perceived quality of spaces for a diverse range of activities. For example, there is evidence that wildlife encounters are preferred by employees to be near their work settings.[411] Thus, for some activities, the presence of wildlife promotes the use and positive experience of spaces, as well as provides a range of benefits, as discussed in Section 9.2.3. Moreover, by designing spaces to provide habitat for wildlife, the ecological behavior of occupants may be improved, the use and perceived value of the space may be increased, and the biodiversity of the local ecosystems can also be enhanced.

However, it is important to note that these benefits can be attained only if the habitat patch is designed effectively. Moreover, a number of design issues must be carefully considered when designing for biodiversity, in order to generate a positive outcome. For instance, the results of existing literature indicates that the development of habitat for indigenous keystone or umbrella species, as well as endangered species, contributes to a greater valuation of these species and their habitats by the local people, by increasing the frequency of interactions between these species and the local community.[383] As discussed in Section 9.3.4, personal interaction with these species may promote their conservation. Existing research also indicates that design for indigenous species interactions may improve the biodiversity and ecological integrity of local ecosystems. This is because the provision of habitat for these species inherently provides habitat for all the species that these species depend on, or that have similar requirements but smaller home ranges.[383] However, care must be taken to ensure that negative interactions with local species aren't developed. All too often design for biodiversity within urban core ecosystems leads to ecological traps, as well as sustains common species populations that compete with endangered and core species for resources within the urban core ecosystem and surrounding natural ecosystems, among other problems.[36] These issues are discussed in more detail in Chapter 11.

Furthermore, it is important to note that people can also be negatively affected by the presence of animals that are perceived to be aggressive or dangerous, such as some predators, if their presence is unexpected or undesired. Furthermore, even non-threatening animals, such as birds, that display aggression have been found to be perceived negatively, and do not generate the positive benefits that positive wildlife experiences provide.[375] As discussed in more detail in Chapter 11, the presence of predators in urban areas is commonly due to a lack of habitat and resources in their original natural environment. This problem is exacerbated as urban sprawl increases within a region. If predators are provided adequate resources and habitats outside of urban areas, than their presence within urban areas becomes largely a design issue. For example, the connections between constructed and natural ecosystems should be designed to prevent common species in urban core ecosystems from entering natural ecosystems that are outside urban areas, thereby inhibiting their tendency to compete for the resources of core and endangered species, including predators. Nevertheless, expected, safe experiences with predators, such as in zoos, have been found to positively affect people's behavior.[93] Positive experiences with predators in natural environments may also promote the valuation of the species by people, such as through safaris, although these types of experiences are typically more dangerous and promote the disturbance of natural ecosystems. Nevertheless, further research into the potential benefits of safe interactions in natural areas, such as safaris and observation towers, may provide interesting results.

§ 9.4 Design for resource consumption behavior

This section investigates the potential of the design of constructed environments to reduce resource consumption. The design of constructed environments inherently addresses individual and community scale resource consumption, by influencing the experiences of individuals, as well as contributing to the resource consumption of local and global communities. A number of design strategies have been identified by existing literature to be effective in promoting resource consumption behavior, and are reviewed in the following subsections.

It is important to note that these design for resource consumption behavior strategies are inherently interrelated, and the incorporation of more than one of these strategies into the design of constructed environments can be mutually beneficial, in terms of promoting diverse ecological behaviors, as discussed in Section 9.2.2. For instance, the design of constructed environments to promote social norms can also support the development of positive behavior habits. Furthermore, the following design strategies, in some cases, can also be effective at promoting non-resource consumption oriented ecological behaviors, as well as improve the ability of various activities to promote ecological behavior.

§ 9.4.1 Eliminate barriers + provide resources

The results of existing research suggest that some of the most effective methods to change an individual's behavior is to remove factors and barriers that inhibit ecological behavior, as well as promote factors that are conducive to ecological behavior.[319, 419] To this end, extant research that has evaluated the validity of the Theory of Planned Behavior (TPB) suggests that an individual's behavior is partly based on reasoned choices that are based on the option that provides the greatest benefits at the least cost, in terms of money, effort, and/or social approval.[7, 297, 419] In accordance with this theory, design can help ecological behaviors be perceived to be more valuable and attractive to individuals, and thereby more likely to be engaged by individuals, by making ecological behavior choices less expensive, more attractive, more convenient, more comfortable, and more beneficial than their non-ecological alternative solutions.

§ 9.4.1.1 Constructed environments as intermediaries

The design of buildings, building systems, and municipal infrastructure inherently determines a substantial portion of their ecological footprints, as well as to some extent, the ecological footprints of their occupants. For example, the water consumption rate of the toilets in an office building are typically outside the control of the occupants, and yet it influences their daily water consumption rates. The design of buildings to improve their ecosystem functions is discussed in more detail in Chapter 10, but it's important to note in this section that the ecosystem functions of buildings inherently influences the ecological behavior of their occupants. Moreover, the ecological functions of buildings are partially a design issue. For instance, as discussed in Chapter 5, workspaces that are designed to incorporate dense vegetation have been found to be able to reduce the energy consumption and carbon emissions rates of buildings, by improving occupant thermal comfort and reducing the heating and cooling demand of the building.[293] In addition, the presence of plants in workplaces has also been found to reduce occupant demand for artificial lighting, as discussed in Chapter 3.[204]

§ 9.4.1.2 Constructed environments as amplifiers

It is important to recognize that some services, spaces, and activities inherently promote the consumption and use of other resources, similar to a magnifying effect. This effect can be positive and negative. For instance, the presence of showers within an office can, in some cases, promote the use of bicycles. In addition, hot desk work spaces promote the use of laptops, and can reduce the use of speakers and other typical workstation accessories. At the same time, printers promote the consumption of paper and ink.

§ 9.4.1.3 Constructed environments as determinants

In some cases, the available options to achieve a goal determines one's behavior, sometimes without the individual being consciously aware of their 'decision'.[319] For example, there is not always a possibility to conduct a behavior in an ecologically positive manner. Sometimes an ecological option or resource is not available, such as when public transportation or recycling has not been provided in a municipality.

In contrast, there is evidence that the availability of an ecological behavior option can sometimes re-orient a person's decision making focus from a hedonistic and self-gain perspective to a social norm perspective, thereby improving the chance that they behave in an ecological manner.[186] This potential behavior shift inherently depends on the quality, ease of access, cost, comfort, convenience, and knowledge of the available options. For instance, the quality of the available options partly affects people's behavior choices, through the offer of a more comfortable or inexpensive option, or on the other hand, a very challenging or effortful option.[319] To this end, environments can be designed to provide materials and services with lower ecological footprints than are currently available in the local community. For example, constructed environments can include agricultural and medicinal vegetation to provide low cost, local, organic food and medicinal resources to the local community.

§ 9.4.1.4 Design constructed environments as determinants, intermediaries + promoters

Therefore, design can help make ecological behavior options more salient in terms of cost, comfort, and convenience, through a range of methods. For example, public and commercial buildings, as well as municipal infrastructure, can provide eco-friendly services that may be cost prohibitive or difficult to achieve at the scale of the individual, or services and processes that inherently require municipal scale investment and development that may not be already present. For instance, the provision of a composting center can provide opportunities for individuals who do not have access to a garden to compost their organic waste. In addition, the design of constructed environments can provide access to activities that are not accessible to some individuals, as well as remove barriers for engaging in specific activities, such as providing park space as an alternative to prohibitively expensive private gyms in low-income areas. Thus, the development of constructed environments that provide greater benefits, value, convenience, comfort, activities, and more ecologically beneficial resources and infrastructure to the local community have a key role to play in generating higher quality, more ecologically sustainable communities and individuals.

§ 9.4.2 Generate positive habits + mitigate negative habits

People form habitual responses for a diverse range of situations. Habits tend to be generated when people frequently act in the same manner in response to a particular situation. The more frequently the situation and response occurs, the stronger and more accessible the association becomes, and the more likely one will act accordingly.[419] When a habit is developed, people act based on their developed automated cognitive processes, instead of via decision based processes.[1] Thus, ecological behavior can be promoted by providing opportunities for ecological behavior to become habitual, such as providing access to recycling and compost facilities. Furthermore, positive habits can be promoted by providing opportunities for people to have repeated, positive experiences when conducting ecological behaviors

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and activities, as well as when inhabiting natural environments. By making participation in ecological behavior and activities a positive experience, repeated participation in these behaviors and activities by individuals is promoted, as well as the development of positive habits. For instance, by providing natural environments that are designed to conduct a diverse range of activities within a community, occupants may over time form habits of conducting these activities in natural environments. These frequent experiences with natural environments and processes also promote ecological behavior and valuation of natural environments, as discussed in Section 9.2.3, as well as encourage the development of positive social norms, which is discussed in more detail in the next subsection.

The alteration of existing habits, such as negative habits, may be more difficult. For instance, extant research suggests that existing habits may only be reconsidered when the context changes significantly enough to require individuals to temporarily suspend their developed habitual response to a given situation.[162] For example, reducing the quantity of waste bins in an office building, as well as locating recycling and compost bins in more convenient locations and designing them to be more visible, may help reduce occupant waste. As discussed in Section 9.4.1, the design of constructed environments provides opportunities to make ecological behavior more pleasurable, convenient, and comfortable than non-ecological behavior, which may in turn promote the development of positive habits, as well as the alteration of existing negative habits. Moreover, design strategies for changing existing habits may be more effective when combined with perceived effectiveness strategies, such as making occupants more aware of the results and effects of their waste consumption, as well as the positive effects of recycling and composting. To this end, design for the perceived effectiveness of ecological behavior is discussed in more detail in Section 9.4.4. In order to determine how to effectively alter existing habits, one should consider how the habits are formed, reinforced, and sustained in their daily routine.[419] In addition, certain types of feedback have been found to be effective in altering specific types of habits, which is discussed in more detail in Section 9.4.4. In cases where altering negative habits may not be feasible, the design of environments can be developed to mitigate the opportunities for occupants to conduct negative habits.

Thus, the design of constructed environments provides diverse opportunities to generate new, positive experiences that promote the development of beneficial habits, as well as opportunities to change and mitigate developed negative habits. Furthermore, the development of positive habits, and the alteration of existing negative habits, can also promote positive social norms and mitigate negative social norms, which is discussed in more detail in the next subsection.

§ 9.4.3 Promote positive social norms, role identities + self-identities

There is substantial evidence that people partly regulate their behavior based on perceived social norms.[89, 90] Generally, there are two types of social norms. Injunctive norms refer to perceptions of which behaviors are approved or disapproved of by society, while descriptive norms refer to perceptions of which behaviors are common or typical. It is important that design teams consider both descriptive and injunctive norms, as existing research has found that some behaviors and design solutions can have contradictory effects from a descriptive and injunctive norm perspective, and thereby be rendered ineffective. For example, by promoting the idea that throwing organics in the trash is a common behavior, instead of showing it is common and socially acceptable to compost one's organics by providing public compost bins, people may be more likely to throw their organics in the trash. This is because, in this case, throwing the organic waste in the trash is perceived to be the common action of the community, even if it is considered a negative behavior from an ecological perspective.[90] Thus, environments that are designed to reinforce, illustrate, or provide examples of positive ecological behaviors and processes being common or approved of by the local community may promote ecological behaviors in individuals. For example, by providing a compost facility within an urban core ecosystem, people will see others bringing compost to the facility, and may thereby view composting as a socially approved and common practice.

Similarly, TPB behavior models have been found to be more accurate when they include an individual's social identity, or perceived sense of belonging, and similarity, to a specific social group. Thus, individuals tend to act in agreement with which they perceive their social groups would act in a similar situation.[7, 297] Hence, design strategies for social identity are quite similar to design for social norms, and can be effective.

Furthermore, Mannetti (2004), among others, found evidence that people were more likely to perform an action if it agreed with their definition of their self-identity, which is who they think they are or would like to be.[297] People's decisions were also found to be partially dependent on an individual's role identity. An individual's role identity is their definition of self as a person who performs specific social roles or a set of behaviors that are expected of a person who has a specific social status, such as a mother, community activist, hiker, environmentalist, etc. To this end, Davis et al. (2009) found that people who perceive themselves as directly associated with nature are more likely to participate in ecological behavior.[112] Furthermore, there is evidence that individuals who perceive the effects of their resource consumption exhibit greater ecological behavior. This is because these perceptions promote individuals to perceive themselves as directly associated with the effects of their resource consumption. These issues are discussed in more detail in the perceived effectiveness subsection of Section 9.4.4.

Therefore, design for social norms, role identities, and self-identities can promote ecological behavior both directly and indirectly. For instance, the provision of natural environments for a diverse range of activities will inherently promote social norms indirectly, by fostering the perception that conducting activities in natural environments is socially approved and common practice. This perception, in turn, may promote individuals to have repeated, positive experiences in natural environments, which would inherently promote individuals to conduct ecological behavior, develop emotional attachments to nature, and develop positive habits. In addition, these types of positive experiences would also generate a number of physiological and psychological benefits for the occupants, as discussed in Sections 9.2.3, 9.3.1, and 9.3.6, as well as Chapter 6. Thus, by providing frequent and diverse opportunities for people to interact with natural environments, resources, and resource consumption processes through a range of activities, they may begin to identify themselves, their social roles, and social norms as more closely related to the natural environment and various ecological behaviors. This may, in turn, increase their propensity to conduct a diverse range of ecological behaviors, potentially generating a recursive nature-experience feedback loop, as discussed in Section 9.2.5.

§ 9.4.4 Provide interactive, tailored feedback

§ 9.4.4.1 Exploring effective types of feedback

Three common strategies employed to improve the ecological behavior of individuals, in terms of personal resource consumption, are: providing information, rewarding or punishing behavior, and providing feedback.[419] However, existing research on resource consumption behavior indicates that providing information tends to raise knowledge levels, but does not typically result in behavior changes.[2, 419] Rewards have been found to be more effective than punishments, but rewards have been found to typically be effective only in the short term.[168] In contrast, feedback has been found to be the most successful general strategy, in terms of changing the resource consumption behaviors of individuals.[2, 181, 390, 419]

Feedback enables people to be more conscious of the relevance and effects of their behaviors.[477] In general, the more frequent the feedback, the more effective it has been found to be. Furthermore, feedback has been found to be most effective when it is given directly after a behavior is conducted.[2, 168, 181, 319, 477] This direct feedback promotes the development of positive habits over time.[181] In addition, as discussed in Section 9.2.2 providing feedback has the potential to generate positive spillover effects and mitigate negative spillover effects. For example, providing feedback on the rates of resource consumption of an individual appliance can also influence occupants' rates of resource consumption, in regards to their use of other appliances. Thus, providing feedback can have a potential magnifying effect, as discussed in Section 9.3.2. Moreover, feedback has been found to be more effective when it provides personalized feedback, compared to non-tailored feedback.[3]

Although existing research on the effectiveness of energy and water monitors have found efficiency gains can be achieved without the incorporation of goals, there is evidence that the effectiveness of feedback is improved when it is interactive. For instance, Gregory and di Leo (2003) found that people that are more directly and actively interacting with resource consumption decisions consume less resources.[181] Thus, personal interactions with resource consumption processes promote specific ecological behaviors.

Moreover, interactive feedback has been found to be successful when it is combined with behavior and resource consumption goals.[3, 242, 304, 477] This evidence is in accordance with the feedback intervention theory (FIT) outlined by Kluger & DeNisi (1996), which suggests that goal setting and acceptance improves the effectiveness of feedback.[251] For instance, McCalley (2002) found that by setting goals, the participants' attention and efforts were directed to activities related to the particular goal of the study. Setting goals also encourages users to make their goals more explicit.[304] In addition, feedback can interrupt one's behavior and habits by making a specific goal more salient, thereby attracting a person's attention and effort away from their typical goal to the feedback related goal.[251] However, it is important to note that the effectiveness of setting goals is partially related to an individual's personality. For instance, McCalley (2002) found that self-motivated people saved more energy when they set their own energy conservation goal, and more socially oriented people saved more energy when they were assigned a goal.[304]

Feedback has been developed in many forms, and with technology advances, there are growing opportunities for developing innovative, effective forms of feedback. The following subsection reviews the results of the general types of feedback that have already been developed and evaluated, as well as proposes several promising innovative methods to incorporate feedback into the design of building environments, based on evidence from existing research.

§ 9.4.4.2 Effectiveness of displaying resource consumption

Existing research on energy consumption feedback displays have found appliance energy use to be reduced by as much as 21.0%, as well as to be effective in reducing overall home energy consumption rates.[2, 3, 143, 304] Although research on water conservation display effectiveness is not as robust as research on energy model displays, extant research indicates that visual water usage displays for specific appliances can be effective at reducing appliance water consumption rates by approximately 10.0-27.0%, even without incorporating opportunities for users to set water use goals on the devices.[242, 477] Furthermore, existing literature suggests that appliance specific feedback, rather than overall building resource consumption feedback, is more effective. This is partially because appliance specific feedback provides more direct feedback that allows the user to perceive the cause-effect relationships of their behaviors more legibly.[477] This effect is discussed in more detail in Section 9.4.4.4.

However, there has not been much research on the effectiveness of different types of feedback displays. For example, Jain et al. (2013) found representing the energy consumption rates of individual residences with the equivalent number of trees that are required to absorb the energy related CO_2 emissions of the residences was significantly more effective than providing feedback in terms of units of energy.[224] In contrast, Chiang (2012) found evidence that suggests that people respond more to numerical feedback displays than more abstract displays, although the participants' actual energy consumption rates weren't evaluated in this study.[87] In parallel, there is also existing evidence that indicates that feedback related to the effects of resource consumption on natural ecosystems can be effective, as discussed in more detail in Section 9.4.4.4. Thus, further research is necessary to determine the most effective feedback representation methods.

§ 9.4.4.3 Group + comparative feedback

Comparative feedback has been found in a number of studies to be effective in reducing people's energy consumption rates, among other ecological behaviors.[2, 319] For instance, existing research on the effectiveness of various energy consumption feedback strategies on office building occupants has found that comparative feedback can be an effective design strategy, depending on the context. The development of effective resource conservation behavior design strategies in non-residential buildings are particularly important, as the occupants of non-residential buildings typically are not directly responsible for resource costs, rarely have access to information on the quantities of their personal resource consumption rates within the building, and may perceive their own resource consumption compared to the overall consumption of the building as negligible.[79]

Although effective resource consumption feedback design strategies in non-residential buildings have received relatively scant research attention, existing literature provides a number of insights.[79, 188] For instance, Gulbinas (2014) found that office building occupants that were provided feedback on the rate of their personal energy consumption, as well as the energy consumption rates of their colleagues, saved substantially more energy than occupants that were only provided feedback on the rate of their personal energy consumption, and even more than occupants that were not provided any energy consumption feedback.[188] Siero (1996), among others, found similar results.[79, 405] These findings are in agreement with existing research on the potential effects of social norms on people's ecological behavior, as discussed in Section 9.4.3. Thus, design solutions that provide opportunities for occupants to compare their rates of resource consumption and behavior to their peers may generate positive social norms and help promote ecological behavior.

Moreover, Gulbinas (2014) found that providing comparative feedback to office building occupants was more effective than providing comparative feedback to occupants of single family residences in existing studies. This contrasting effect may be because office building occupants may have more direct social connections with their colleagues than neighbors within a suburb. Alternatively, this finding may relate to the discussion in Section 9.4.4.1 about individuals that are more socially oriented save more energy when they are assigned a goal. In other words, comparative feedback may provide a goal for individuals to achieve: to reduce their energy consumption rate more or equal to the energy consumption rate of their colleagues. Thus, individual feedback may be effective for self-motivated individuals, and comparative feedback may be more effective for socially oriented people. However, the effects of the participants' personalities on their rates of energy consumption were not accounted for in the office building feedback studies. Regardless, existing literature suggests that comparative feedback is an effective design for resource consumption strategy within office buildings.

§ 9.4.4.4 Perceived effectiveness: Exploring the potential benefits of demonstrating the effectiveness of ecological behaviors through design

Existing literature suggests that people may doubt the adverse effects of climate change and resource consumption partially because the predicted long term effects of these issues are typically not evident in the daily experiences of individuals and communities.[390] Thus, when people make positive changes to their behavior, the positive effects of their behavior are not always readily evident. In other words, people are not always able to perceive the predicted local and global effects of non-ecological behavior in their own lives, as well as the benefits of their individual and cumulative ecological behaviors.

Nevertheless, there is evidence that when people perceive their actions to contribute to solving a specific environmental problem, they are more likely to engage in ecological behavior.[461] This is partially a design issue. For example, if people bring organic waste to a compost facility, and community gardens are provided at the facility, people may perceive a direct benefit of their organic waste contribution. To this end, further research is necessary to determine effective design methods and solutions that provide opportunities for people to perceive the effects of their behaviors, both negative and positive, in ways that positively affect their behaviors.

For instance, direct sensory experiences of the long term effects of climate change, through the viewing of the movie, The Day After Tomorrow, have been found to increase people's belief in climate change.[271] This may be because these types of experiences may help people better conceptualize and perceive the cause-effect relationships of their behaviors, which can promote ecological behavior.[319] Similarly, the ecological processes that sustain urban areas are typically hidden from perception at multiple scales, such as the effects, scale, and quantity of individual, building, city, regional, and global scale water consumption.[320] This constructed separation makes it difficult for people to perceive, and understand, the negative effects and scale of their resource consumption and behavior on the natural environment, as well as on their own communities.[296] Since repeated, positive interactions with nature have been found to promote individuals to conduct ecological behavior, as discussed in Section 9.2.3, it is probable that the development of responsive environments that promote interactions between occupants and the potential and actual ecosystem functions and services nature provides, as well as the inherent resource consumption processes of built environments, will also promote ecological behavior and awareness.

Extant research supports this hypothesis. For instance, experience with recycling activities has been found to change people's understanding about the consequences of recycling.[346] In addition, by developing these types of spatial feedback and interactions into the constructed environments that people inhabit on a daily basis, additional opportunities for people to form an emotional bond and cognitive interest with natural environments, processes, and resources are created. These types of experiences have been found to promote ecological behavior, as discussed in Section 9.3.1. Furthermore, these types of interactions may cause people to identify themselves, their social roles, and social norms as more closely related to the natural environment, resources, and processes, as well as various ecological behaviors. This may, in turn, increase their propensity to conduct a diverse range of ecological behaviors. However, the development of EAN and ecological behavior by occupants through various types of positive, frequent interactions with diverse resources and processes have not yet been thoroughly evaluated through research. To this end, based on the evidence presented in this section and chapter, the effectiveness of various design solutions to generate these types of symbiotic interrelationships merits further research.

Design can also help individuals conceptualize and comprehend the cause and effect relationships of their actions in tangible, effective ways, through the design of direct sensory experiences. This developed understanding has also been found to promote ecological behavior.[319] For example, seeing the quantity of water occupants are consuming from a water tank as they use the bathroom sink directly connects occupant behavior to their rates of resource consumption. The potential of feedback mechanisms, such as these, to promote ecological behavior is discussed in more detail in the previous subsections of Section 9.4.4. Thus, community based infrastructure can also reduce the perceived and objective individual costs of ecological behavior and processes, as well as reinforce social norms, as discussed in more detail in Section 9.4.3.

Thus, there are a number of benefits for developing multiscalar design solutions, both at the city and individual building scale, that increase the opportunities for occupants to interact with, and more directly understand and perceive, the effects and quantity of the ecological footprint of their local urban area, as well as their individual ecological footprint. For instance, building processes and systems, as well as natural systems, components, and processes, can be designed to allow occupants to see, feel, touch, taste, and/or hear, and consequently understand, how the systems and processes function, as well as the negative consequences of non-ecological resource consumption, and the positive effects of ecological resource consumption. This can be achieved through the development of opportunities for direct and indirect engagement of occupants with building and city infrastructure and processes. For instance, natural systems, components, and processes can be incorporated into building and city infrastructure and processes, in a manner that raises occupants' awareness of their potential and actual ecosystem functions and services. Furthermore, these types of natural ecosystem and process integrations into constructed environments would also increase the contribution of buildings and cities to the ecological functions and biodiversity of the local natural ecosystems. Moreover, it is important to note that perceiving and experiencing resource processes can result in changes in one's behavior, in relation to other resource consumption behaviors, as well.[319]

At the individual building space scale, the building's infrastructure and processes can be incorporated into a building space either indirectly as a component of the space or directly through the development of occupiable infrastructure spaces, such as a winter solar collecting greenhouse or occupiable thermal mass.[296] For example, a shallow pool of water containing the quantity of water consumed each month by the bathroom fixtures could be situated outside an office bathroom. If the pool of water functions as the water supply for the bathroom, the water level could reduce as it is used by the occupants. This is an example of integrating the building's infrastructure indirectly as a component of a space, in order to provide occupants feedback on their resource consumption. Furthermore, bodies of still and falling water can attract occupants to inhabit a space, and in doing so, foster social interactions.[475] Thus, this type of space would generate an informal break space for the inhabitants. As building occupants inhabit the space and perceive the water level fluctuating throughout the month, as well as the water's visual and light reflections, they are directly engaged with the spatial quantity and rate of their water resource consumption, as well as the sensuous benefits of the resource, which are typically withheld from view.[296] If this pool of water is treated as a natural pond, replete with water filtering plants and aquatic animals, this space will also function as an example of the ecological functions natural ecosystems provide.

By allowing occupants to interact and perceive their quantities, rates, and effects of resource consumption, as well as the potential ecosystem services and functions nature can provide, and by utilizing these resources as sensuously engaging, fascinating stimuli of the occupied environment, occupants may become more sensitive to their personal rates of consumption, more knowledgeable about the cause and effect relationships of their resource consumption, more ecologically aware, and more perceptive of the potential social, natural, and economic benefits and value of symbiotically interacting with natural environments, processes, and various resources.[296] If this effect is internalized by the occupants through the development of habits, social norms, and positive ecological behavior, it may influence the occupants' overall resource consumption, rather than just their resource consumption behavior while they are inhabiting the building. Thus, specific designs for resource consumption behavior have the potential to generate spillover effects, as discussed in Section 9.2.2. Therefore, there is a potential magnifying effect for designing for resource consumption behavior. Moreover, it is evident that there are a number of opportunities for further research into the potential of spatial design to promote ecological behavior.

§ 9.4.5 Design for possible futures

Furthermore, based on the results of existing research, the development and communication of alternative possible high quality and high performance futures for local building, infrastructure, and community projects to the local community may be effective in motivating individuals and communities to develop more ecologically positive buildings, infrastructure, and communities.[212, 271] This is because these types of projects, which can be defined as *possible future* projects, demonstrate the potential value and quality of their communities, the effectiveness of possible solutions, as well as call attention to the currently negative performing parameters of their communities. Thus, the development and exhibition of alternative building, infrastructure, and community design solutions that improve the quality of the built environment and local community, provide viable solutions to ecological problems, and make the problems, quantities, and scale of people's resource consumption perceptible to the local community, may promote communities to value and invest in these types of higher quality and higher performance design solutions.

§ 9.4.6 Design for figurative cues

In addition, there is evidence that figurative cues and primes may be able to change people's behavior and perceptions. For example, Gueguen (2012) conducted a study that found that people that viewed dead plants, compared to live plants, believed more in global warming. Furthermore, an increase in the quantity of plants was found to increase the participants' belief in global warming.[187] In another study, an increase in the temperature in an outdoor environment resulted in an increase in the participants' belief in global warming.[229] From a design perspective, figurative cues and primes can be incorporated into the design of built environments in ways that promote ecological behavior. For instance, the design of a desert environment directly outside, or inside, a bathroom may reduce the rate of water consumption of occupants.

§ 9.4.7 Design for positive interactions between people, resources, and resource consumption processes

Thus, by designing for opportunities for individuals to have positive experiences and interactions with resources and resource consumption processes, people may generate an emotional bond with these resources, similar to the design for EAN strategies that are discussed in Section 9.3.1.[86, 95, 112, 237, 329]

§ 9.5 Designing activities to promote ecological behavior

Natural environments can be beneficial settings for conducting a diverse array of activities, in terms of their potential to provide economic, social, and ecological benefits. For example, extant research on ecosystem services, recreation, and restorative environments have identified a diverse range of cultural activities that people value conducting in natural environments, and that benefit from being conducted in natural environments. For instance, natural environments have been found to function well as spaces for finding artistic inspiration, gardening, exercise, healing, spaces to learn about the history and processes of the local natural ecosystems, recreation, tourism activities, spiritual and religious inspiration activities, and spaces for relaxing and socializing.[95, 474, 486] Participation in a number of these activities in natural environments have been found to directly promote ecological behavior.[95, 113, 198, 430, 474] Moreover, as discussed in Section 9.2.5, existing literature suggests that frequent participation in activities in natural environments that result in positive experiences, as well as benefit from being in natural environments, promote ecological behavior.[95, 113] Thus, the successful development of activities that promote ecological behavior inherently requires design teams to determine which activities and benefits of natural environments are needed, and will support, the local community.

Furthermore, it is important to note that natural environments can benefit a more diverse range of activities than existing research has evaluated. For example, as discussed in Section 9.4.3 and Chapter 7, a number of different natural environments have been found to be beneficial for conducting a variety of work tasks. Further research into the types of activities people benefit from conducting in natural environments, including previously unconsidered building programs and activities, may yield additional beneficial interrelationships between communities and natural environments. Furthermore, although a number of activities may benefit from being conducted in natural environments, further research is necessary to determine the relative effectiveness of conducting various activities in natural environments, in regards to promoting ecological behavior.

From a different perspective, the combination of activities within individual spaces can be mutually beneficial. For example, as discussed in Chapters 6 and 7, the design of individual spaces to promote worker performance for multiple work tasks can increase the space efficiency, and therefore cost, of work environments, as well as reduce the costs of developing high quality work environments, such as microforests. Moreover, as discussed in Section 9.2.3, the integration of natural environments, resources, and resource consumption processes into constructed environments that host diverse and numerous activities, can increase the local community's valuation of, and quantity of interactions with, natural environments. These types of integrated design solutions can also increase the community's comprehension and valuation of, as well as quantity of interactions with, the diverse effects and processes that are related to the local community's resource consumption. Moreover, these interactive experiences can generate emotional and cognitive connections between communities and local natural ecosystems and resources, as well as resource consumption processes. These mutually beneficial interrelationships may thereby improve the community's ecological awareness and potential to engage in ecological behavior.[320] Furthermore, as previously discussed in Section 9.2.5, the provision of numerous activities in natural environments may also help mitigate urban sprawl, while also promoting ecological behavior.

An in depth analysis of the myriad of activities that natural environments can be effectively incorporated into is outside the scope of this chapter. For example, a number of activities in natural environments have been found to improve occupants' physical health, such as healing gardens, gardening, and exercise in natural environments. [233, 474] However, the effects of these activities on occupants' ecological behavior has not yet been adequately evaluated. Nevertheless, the following subsections provide examples of the types of activities that have been found to benefit from integration with natural environments, while also improving ecological behavior. Furthermore, it is important to note that a number of the types of experiences discussed in Sections 9.3 and 9.4 are also related to this section, such as restorative environments and resource consumption activities.

§ 9.5.1 Design activities for heterogeneous populations

Cities are typically comprised of heterogeneous populations that have diverse lifestyles, ethnicities, and age groups, which have been found to benefit from varying activities, as well as different spatial qualities and environments, for a range of activities.[42] However, there has not been much direct research conducted on the effects of social and demographic factors on the ecological behavior of individuals and communities.[240, 283]

Regardless, the design of ecologically beneficial constructed environments need to account for these influential design factors, and incorporate natural environments that will benefit, engage, and support these diverse activities and community groups. Although a review of the potential and found effects of each of these factors is outside the scope of this chapter, this subsection provides a review of several of the different types of groups that have been found to directly affect ecological behavior.

§ 9.5.1.1 Design for different age groups

There is evidence that different age groups prefer different types of environments for different activities. For example, a number of studies have found that children have the greatest preference for being in natural environments.[30, 208, 283] Furthermore, existing research indicates that experiences in natural environments as children are particularly important for promoting ecological behavior.[86] [95] This is partly because individuals' environmental attitudes and behaviors are developed over time, through the development of habits, as well as the influence of social norms and personal experiences, among other factors. For instance, as discussed in Section 9.3.7.3, existing literature suggests that the more people experience a type of environment, the more they prefer and value that environment, which in turn promotes ecological behavior.

In contrast, teenagers have been found to be less interested in natural environments than other age groups. Herzog (2000), among others, suggested that this disinterest may be because teenagers are more concerned with their social environments, such as their clothes, appearance, music, and peer relationships.[30, 208] To this end, White (2013) found that restoration gained from occupying natural environments was the lowest for occupants that were between the ages of sixteen and twenty-four.[474] However, the lack of interest from teenagers may also be a design problem. Perhaps the design of natural environments for teenagers should investigate strategies to design these environments to effectively promote the different activities this age group prefers.

§ 9.5.1.2 Design for group based activities versus individual activities

The design of constructed environments should consider the inherent different design factors that are beneficial for conducting activities for individuals and groups. For instance, Staats (2004) found that experiencing natural environments in groups, as opposed to as individuals, makes people feel more safe, and in turn, more likely to experience mental restoration. In contrast, when individuals feel safe in natural environments, they were found to experience more mental restoration than experiencing natural environments in groups.[417] Thus, the design of constructed environments that incorporate natural environments should take into account how to design the space to promote perceptions of safety by occupants, in order to maximize the benefits occupants acquire from experiencing the space. In another study, an increase in group members resulted in an increase in an individual's attraction to interact with active wildlife. This increase in attraction levelled off when groups were comprised of more than four people, which suggests that larger groups may not perceive the physical environment as much as individuals or smaller groups.[121] Furthermore, there is evidence that experiencing natural environments with one's friends and families can increase the benefits natural environments provide.[237] This may be partly because the presence of others can make people feel more secure in natural environments, which may in turn prevent negative associations and emotions within the natural environment.

Therefore, conducting activities in groups may provide opportunities for people to explore environments, and conduct activities, that could be perceived as too dangerous, or wild, to explore by themselves. In addition, the presence and opportunities for social exchange with others may stimulate curiosity and cognitive interest via questions, observations, and discussions with others.[237] Regardless, it is apparent that various individuals and groups respond to environments differently. Hence, the design of constructed environments for various activities are inherently influenced by, and should therefore account for, the potential diverse effects, uses, benefits, and perceived value of environments on various individuals and community groups.

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§ 9.5.2 Environmental education

Existing literature suggests that environmental education (EE) can improve people's ecological awareness and behavior. For instance, Lieflander (2012) found that environmental education increased students' connection with nature.[275] Moreover, Cheng & Monroe (2012) found evidence that nature sleepover camps can be more effective than day camps, because participants have greater exposure to nature.[86] However, since these types of camps require parental approval, it is likely that the home environments of the participants support a positive attitude toward nature, which may be a contributing factor to their finding. Furthermore, a review of existing research on the effectiveness of EE programs to promote ecological behavior by Collado (2013) found the results of existing studies to be contradictory, in terms of the effectiveness and influence of the duration and location of EE programs. For instance, the existing literature that Collado (2013) reviewed did not evaluate the influence of being in nature and the EE programs separately, they did not include a control group of participants being in nature without EE, nor did they evaluate the effectiveness of various EE programs, content, and durations effectively. Based on these findings, Collado (2013) suggested that the contradicting results of extant research indicate that the effectiveness of the various EE programs may depend on the specific content, effectiveness of the teachers, and the location of the EE programs that were analyzed.[95]

In support of these findings, Collado (2013) presented the results of a study which evaluated the effectiveness of an urban environmental education program, a sleepover camp in a natural environment, and a sleepover camp in a natural environment that included an EE program. The children in both nature programs were found to have an increased emotional affinity toward nature, as well as increased ecological beliefs and willingness to display ecological behavior. Interestingly, the EE program did not have a noticeable effect on the environmental beliefs of the participants. Moreover, an increase in the duration of the camp did not have an additional effect.[95] However, the effects of the EE program may have been overshadowed by the effects of being in nature. In addition, the content or duration of the EE program may not have been effective. Regardless, these results indicate that direct experiences in nature are an effective means to promote ecological behavior, and can be a more effective means than some ecological education programs. However, it is important to note that other EE programs that did not incorporate experiences in nature have been found to promote ecological behavior.[95] Thus, further research is necessary to investigate the effectiveness of various EE programs, including their content, duration, location, and teaching methods, as well as the long term effectiveness of being in nature on people's ecological awareness and behavior.

In this respect, a number of activities conducted in natural environments have been found to indirectly promote ecological behavior and awareness, as well as improve the environmental knowledge of participants. Existing research on some of these activities are discussed in the following subsections. These activities combine experience with nature with less structured methods of teaching participants the value of nature, from a variety of performance perspectives. These activities also tailor information about the participants local ecosystems, including their personal effects on, and connection to, the ecosystems. Tailored information has been found to be more effective at promoting several ecological behaviors by a review of the effectiveness of information campaigns by Abrahamse (2007), among others.[3, 419]

Furthermore, these findings are in agreement with the results of the resource consumption literature presented in Section 9.4, which found that the environmental beliefs of individuals do not substantially influence their ecological behavior, in regards to a range of tasks. Nevertheless, direct, tailored feedback on one's behavior did result in ecological behavior.[3, 419] Furthermore, it is important to note that this transference of tailored, local ecological knowledge is not developed through some existing EE programs. Thus, indirect ecological education activities may provide unique opportunities to promote ecological behavior, as well as provide a myriad of social, economic, and ecological community resources and opportunities.

§ 9.5.2.1 Adult social learning

The participation of individuals in a range of nature related social activities have been found to improve participants' ecological knowledge, awareness, and behavior. Some examples are green gyms, public access community (PAC) gardens, and allotment gardens. Through these activities, effective ecological practices, knowledge, and experiences are conferred, improved upon, and retained. These benefits are achieved via the conductance of a number of behaviors in these activities, such as imitation of practices, oral communication, collective rituals and habits, and practical experiences.[42] In addition, garden management practices inherently provide agricultural products and additional ecosystem services, such as air and water filtration. Furthermore, these types of activities provide opportunities for individuals to interact with others and form social communities, conduct physical exercise, relieve stress, as well as perceive ecological behavior as a social norm.[33] Although further research is necessary to determine the effectiveness of these various programs, there is evidence that involvement in the maintenance and development of local natural environments imbues participants with a greater knowledge of ecosystem services, as well as results in greater care, valuation, and maintenance of local natural environments.[42, 132, 137, 420] For instance, Ernston (2013) found that allotment gardeners had greater local ecological knowledge and a wider range of effective ecological management practices than cemetery and park managers.[132] This finding suggests that the integration of social learning and nature management can be more effective at promoting ecological behavior and constructing effective natural environments. Thus, natural environments can be designed in ways that teach people how to manage ecosystems through their actions and foster ecological behavior, while also providing opportunities to conduct psychologically and physiologically beneficial activities, similar to the discussion in Section 9.2.3.

§ 9.5.2.2 Citizen science

Local communities are increasingly becoming active contributors to the development of conservation science research. For instance, volunteers are assisting researchers by collecting research data through observation and exploration of their local ecosystems. Volunteer programs have also been successfully developed to actively restore and expand local ecosystems, such as the Chicago Wilderness Project.[320] It is important to note that the aid of volunteers provides opportunities for researchers to develop larger scale, more valuable, and more successful studies and ecological conservation projects than in some cases might otherwise be possible. These projects provide a large quantity of field workers for researchers, and generate an active dialogue between ecologists and the local community. Through participation in these collaborative projects, the public is able to better understand how these research processes work, and the value of ecological research. Moreover, these collaborative endeavors have been found to raise the participants' and local communities' awareness of conservation issues and the value of local ecosystems and species, as well as promote a variety of both high and low effort ecological behaviors.[137, 250, 354] Thus, the development of these types of local activities can develop magnifying effects.

Indeed, the results of these citizen science programs indicate that they may be more effective at raising ecological awareness and behavior than general classroom ecological education programs, and they provide evidence that direct engagement with natural environments may be more effective than general ecological education endeavors.[137, 250] For example, these types of activities can provide more direct experiences and interactive, tailored information about the value of local natural ecosystems to the participants. In addition, these types of activities can provide clear, direct opportunities to conduct ecological behavior. To this end, these types of projects provide opportunities for participants to perceive the effectiveness of their ecological behaviors on the local natural environment, as well as in some cases to perceive the negative effects of non-ecological behaviors and resource consumption behaviors and processes. For instance, after participating in a coral reef fisheries assessment project in Hawaii, the locals became interested in co-managing the established coral reef fisheries, and developed community based sustainable fishery plans.[250] Thus, these types of projects provide opportunities to promote ecological behavior through a diverse range of methods that are discussed in the other sections of this chapter, including providing personal, positive experiences in natural environments, social learning, promoting social norms, positive habits, providing feedback, and allowing participants to perceive the effectiveness of their ecological behavior.

§ 9.5.2.3 Business integration

Natural ecosystems can provide a number of financial opportunities to local communities. However, local communities do not always have access to, or in some cases even awareness of, these opportunities. To this end, there is evidence that raising awareness of, and providing access to, these types of mutually beneficial opportunities can be effective in some cases. For example, Rosenzweig (2003) provides a broad range of projects that benefit natural ecosystems and human communities.[384]

As a specific example of business integrated ecological behavior, Namibia has been relatively successful at conserving their rhinoceros population. A key component to their success has been making the local inhabitants of the land adjacent to the conservation areas the owners of the conservation lands.[413] It is important to note that some of these locals were previously poachers. By running eco-tours of the conservation lands, the locals were able to maintain a suitable lifestyle without resorting to poaching. In addition, by tying the livelihoods of the local inhabitants to the survival of these species, the locals have become active protectors of the land. The result has been a substantial increase in the populations of a diverse range of endangered and native species, including the rhino. In addition, the ecological awareness and valuation of nature by the community has increased considerably.[413] Thus, the incorporation of commercial businesses with natural ecosystems can be an effective strategy that raises awareness and promotes ecological behavior in regards to local ecosystems, provides economic and social benefits to local communities, as well as improves the biodiversity and ecosystem functions of local ecosystems.

§ 9.5.3 Office work environments

The provision of natural environments around offices, and potentially integrated within offices, can provide a number of benefits to building owners and employees, while also promoting ecological behavior. For instance, the presence of vegetation in the workplace has been found to improve worker performance, space use rates, employee absence rates, well-being, and comfort.[199, 241, 254, 358, 418] At the same time, Mangone (2014) found the integration of natural environments into office buildings can reduce the rate and cost of energy consumption of buildings, while simultaneously improving worker performance and comfort.[292]

Furthermore, as discussed in detail in Chapters 6 and 7, there is evidence that the integration of various types of natural environments into office buildings can benefit the performance of office workers in regards to a number of work tasks. Moreover, office workers have been found to prefer opportunities for interaction with wildlife,[239] as well as prefer more natural landscapes adjacent to their office than the typical extensive lawnscapes.[411] At the same time, existing research indicates that a number of ecological behaviors can be promoted by increasing the frequency of positive interactions of office workers with natural environments and resource consumption processes, as discussed in Sections 9.2.3 and 9.3.1.

§ 9.6 Chapter Conclusion

Thus, the design of constructed environments directly affects the behavior of the occupants. Moreover, there are a diverse array of design strategies that can be incorporated into the design of constructed environments to effectively promote various ecological behaviors. Furthermore, the design of constructed environments can promote numerous ecological behaviors, while at the same time, improve the economic, social, and ecologic performance of the project and local community. To this end, the design of constructed environments, in regards to one of these performance parameters, can inherently improve the others. In addition, the results of this chapter indicate that design strategies that focus on addressing multiple performance parameters can improve the effectiveness and feasibility of the design solution, in terms of addressing each of the individual performance parameters.

However, it is important to note that relatively few effective design for ecological behavior strategies have been identified in existing literature. Moreover, the relative effectiveness of various strategies is currently difficult to determine. Nevertheless, this chapter identifies a number of potentially effective design for ecological behavior strategies that should be further investigated in future design and research projects.

In addition, the design of constructed environments to promote ecological behavior can sometimes also inherently improve the ecological integrity of local constructed and natural ecosystems, by improving the ecological functions and biodiversity of the local ecosystems, as discussed in Chapters 10 and 11. Moreover, design for ecological behavior strategies can be integrated with design for ecological functions and biodiversity strategies, in ways that improve their effectiveness.

From a general perspective, the results of this chapter indicate that the development of constructed environments that promote ecological behavior through the development of environments that have greater benefits, value, convenience, comfort, activities, and more ecologically beneficial resources and infrastructure than typical constructed environments have a key role to play in generating higher quality, more ecologically sustainable communities and individuals.

10 Constructing Ecosystem Functions

Exploring the potential of constructed environments to improve the functions of local and global ecosystems

§ 10.1 Introduction

The ecological integrity of an ecosystem is dependent on the long-term functionality and state of its functions.[71, 189, 238] Therefore, an effective design method to improve the ecological integrity of local ecosystems is to assess and address the ecosystem functions of an ecosystem. To this end, this chapter explores the potential of the design of constructed environments to improve the functions of local ecosystems.

§ 10.1.1 Understanding ecosystem functions and services

The results of extant literature indicate that further research is necessary to determine how to effectively assess the influence of the various functions of an ecosystem on its integrity.[71, 238] This issue is discussed in more detail in Sections 10.2.2, 10.2.4, and 10.2.5. Moreover, there is considerable debate among researchers as to the definition of ecosystem functions, as well as to the distinction between ecosystem functions and services. Thus, the following subsections review existing definitions of ecosystem functions and services, while the issues and debates related to the definitions of ecosystem functions and services are discussed in Section 10.2.1.

§ 10.1.1.1 Defining ecosystem functions

Since the focus of this chapter is on the effects of constructed environments on the ecological integrity of local natural and constructed ecosystems, the ecological integrity oriented definition of the term 'ecosystem function' is used within this chapter. Within this context, ecosystem functions can be defined as the ecological structures and processes that occur within an ecosystem.[22, 189]

§ 10.1.1.2 Defining ecosystem services

Ecosystem services can be considered to be the contributions of ecosystem functions, as well as other ecological inputs, to human well-being.[71] Thus, ecosystem functions are necessary for providing ecosystem services. Moreover, the quantity, quality, and rate of provision of ecosystem services to human communities by natural ecosystems are dependent upon the state of their integrity and functions.[238] It is important to consider that the modification of an ecosystem's ecological integrity leads to reductions or increases in its supply of ecosystem services. Furthermore, the evaluation of an ecosystem's functions can indicate the potential of an ecosystem to provide various ecosystem services.[71, 238]

From a consumption perspective, the concept of ecosystem services includes both goods and services collectively, and can be defined as the benefits human communities derive, directly and indirectly, from ecosystems.[16, 27] However, it is important to note that the definition of some types of ecosystem services are currently under debate. For instance, some researchers have suggested that indirect benefits should be defined as ecosystem functions, rather than ecosystem services.[189, 238] These issues are discussed in more detail in Sections 10.2.1 and 10.2.4.

§ 10.1.1.3 Defining ecosystem service footprints

The measure of human demand on ecosystem services can be referred to as their ecosystem service footprint, which is similar to the more common ecological footprint concept. The ecosystem service footprint calculates the area needed to generate the total ecosystem goods and services demanded by humans in a specific area for a specific time period, including the ecosystem services needed for resource consumption and waste assimilation services.[71] In contrast, ecological footprint calculations attempt to quantify the resource consumption and waste assimilation of a community, but have been found in a number of studies to be inadequate in accounting for total human demand on ecosystem services. For instance, ecological footprint calculations typically do not account for the location where ecosystem services are provided.[71, 84, 455] Ecosystem service footprint calculations can be more comprehensive, yet significant barriers to develop accurate assessments remain, which is discussed in more detail in Section 10.3.1.[71, 238]

§ 10.1.2 Defining the current impact of human communities on ecosystem functions and services

Cities typically adversely affect the functions of local and global ecosystems.[9, 463] For instance, the ecological footprints of a number of cities have been estimated to be 500-1000 times larger than their developed areas.[150] Moreover, the establishment of human communities tends to degrade the natural self-repairing capacity of the pre-existing local natural ecosystems, as well as reduce the quantity of ecosystem services that they can provide to unsupportive levels. These negative effects of human development are generated primarily through the degradation, fragmentation, and removal of natural habitat patches and ecosystems, as discussed in Chapter 8.[259, 455] At the global scale, the size and quality of natural ecosystems worldwide are declining substantially, due to increasing quantities of anthropogenic activities negatively impacting local and global ecosystem functions, as discussed in Chapters 8 and 11.[455]

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In parallel, human communities are now consuming natural resources at a faster rate than natural ecosystems can produce. Moreover, the negative effects of human communities on natural ecosystems are so large that the combined ecosystem service footprint of all the human communities in the world is now greater than the quantity of resources that are available on earth.[165, 325] For example, forests are now being demolished faster than they can regrow, and fish stocks around the world are being depleted faster than they are able to replenish themselves.[454] Indeed, Worm, et al. (2006) found that commercial fishing stocks have collapsed in almost one-third of sea fisheries, and that global food fisheries could completely collapse by 2050 if current fishing trends continue.[483]

§ 10.1.3 Defining the potential of constructed environments to improve ecosystem functions and services

It is thus apparent that human communities must reduce their ecosystem service footprints, while also improving the ecosystem functions, quality, and size of natural ecosystems, in order to sustain their demand for ecosystem services. Moreover, by reducing the demand of ecosystem services by constructed ecosystems and improving the ecosystem functions of local and global ecosystems, the ecological integrity of local and global natural ecosystems can also be improved.

Constructed environments and ecosystems can contribute to the ecosystem functions of local and global ecosystems by generating and supporting local ecosystem services and functions, reducing the existing negative effects of constructed ecosystems on the state and functions of local and global ecosystems, and mitigating the ecosystem service footprints of individuals, constructed environments, and constructed ecosystems.

As discussed in Chapter 8, the development of symbiotic interrelationships between constructed and natural ecosystems can help human communities achieve these goals. Furthermore, the mitigation of the negative impacts of constructed ecosystems on the biodiversity of local and global natural ecosystems, as well as positively contributing to their biodiversity, can contribute to the functions of local and global natural ecosystems.[35, 71, 219]

§ 10.1.4 Defining the scope of the research

§ 10.1.4.1 Primary research objective

The primary objective of this chapter is to explore the potential of constructed environments to improve the functions of local constructed and natural ecosystems. In other words, the goal of this chapter is to determine how urban development can improve local ecosystems, rather than negatively influence them. It is important to note that this goal is in stark contrast to the common anthropogenic perspective that design teams and various existing studies have used to address ecosystem functions. This anthropogenic centered perspective values ecosystem functions in terms of their potential to provide benefits to human communities. However, this approach does not lead to effective methods to improve the functions of local ecosystems and reduce the diverse negative effects of human communities on local and global ecosystems.

§ 10.1.4.2 Research boundary limits

This research goal is addressed within this chapter at the scale of individual constructed environments, such as buildings and landscapes. In addition, the contextual focus of this chapter is on constructed environments that are situated within urban core ecosystems, as discussed in Chapter 8. Nevertheless, it is important to consider that the results and discussions within this chapter are often relevant to other contexts and scales as well.

§ 10.1.4.3 Sub-research objectives

In order to design constructed environments to effectively contribute to the ecosystem functions of local and global ecosystems, the potential ecosystem functions that can be addressed must be defined, and the relative value of various ecosystem functions must be assessed. To this end, Section 10.2 provides a review of the general definitions and values of various ecosystem functions and services, as well as assessment methods, that have been identified and evaluated in existing literature. Section 10.2 also identifies existing knowledge gaps within this research domain. Furthermore, Section 10.3 explores the potential of constructed environments to promote the functions of local ecosystems. Section 10.4 discusses potential design issues, and a number of design guidelines, which can aid design teams in developing constructed environments that improve the functions of local ecosystems. A general overview of the structure of this chapter is illustrated in Figure 10.1.

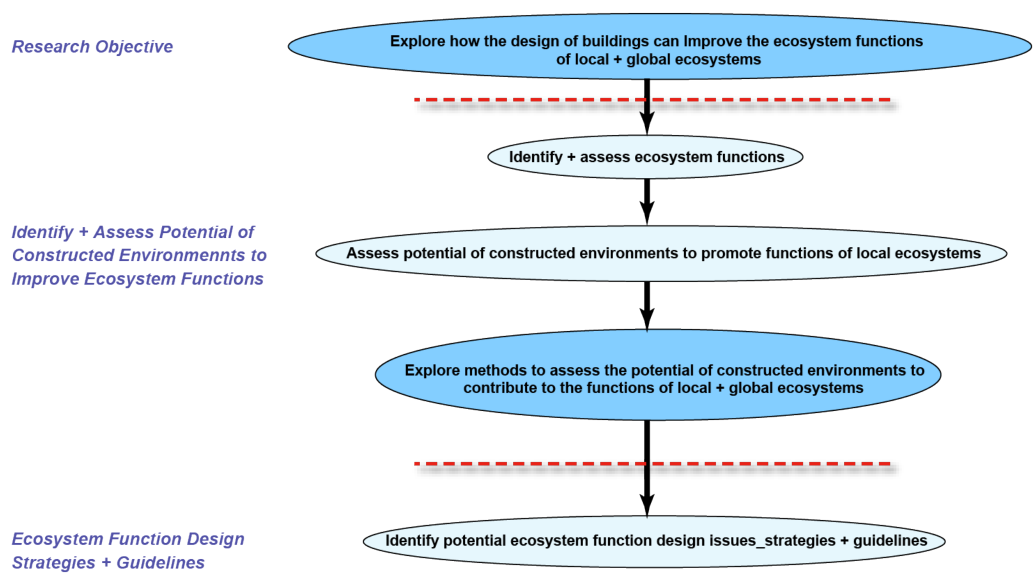

FIGURE 10.1 Constructing ecosystem functions chapter overview

§ 10.2 Identifying + assessing ecosystem functions

§ 10.2.1 Identifying individual ecosystem functions and services

A diverse array of ecosystem services and functions have been identified by extant research, and can be used to help identify and assess the functions and services of ecosystems, as discussed in Section 10.2.2.8. To this end, Table 10.1 provides an overview of natural ecosystem services and functions that have been identified in existing research. A detailed review and description of the various identified ecosystem services and functions is outside the scope of this chapter. Kandziora (2013) and Burkhard (2012) provide more detailed reviews and discussions.[71, 238]

However, it is important to note that there is evidence that it may not be possible to develop a simple, standardized checklist of specific services that ecosystems can support, due to the inherent limitations of extant research, as well as a number of other influential factors.[189, 201] The following subsections review several influential factors that should be addressed when defining individual ecosystem services and functions.

§ 10.2.1.1 Accounting for unknown ecosystem services

It is important to consider that the quantity of identified ecosystem services and functions is expected to increase in the future, due to the continuing identification of new ecosystem services, as well as the development of innovative technology and methods to derive new benefits from natural environments and processes.[201] Thus, design teams should consider how to promote the functions and integrity of local and global ecosystems through existing as well as innovative methods, as discussed in more detail in Section 10.4.6.

§ 10.2.1.2 Categorization of individual ecosystem services

The various individual ecosystem services and functions that have been identified in existing literature can be organized into four categories of ecosystem services: provisioning services, regulating services, supporting services, and cultural services, as shown in Table 10.1.[22]

Regulating services are benefits that people obtain due to the regulation of natural processes, such as water purification.

Supporting services are typically the structures and processes of ecosystems that provide the foundation for other ecosystem services to be generated. For instance, soil formation processes provide natural ecosystems opportunities to provide services such as food.

Provisioning services include all tangible products from ecosystems that humans make use of for nutrition, (economic) processing, and energy use. These products can be traded and consumed or used directly, such as food and minerals.

Cultural services refer to the intangible benefits people receive from ecosystems in the form of non-material experiences within natural environments, such as from spiritual, religious, inspirational, and educational activities.[22] Chapter 9 provides a more detailed review of activities that benefit from being conducted in natural environments.

It is important to note that this categorization method is currently under debate, as discussed in Sections 10.2.1.3 and 10.2.3.

Provisioning Services	Regulating Services	Supporting Services	Cultural Services
Food _Fodder _Crops and livestock *(land and aquatic)*	***Purification*** _Water _Air _Soil	***Soil*** _Formation _Retention _Renewal of fertility _Quality of control	*Recreation and Tourism* *Education and Knowledge* *Aesthetic Value*
Biochemicals _Medicines _Cosmetics _Other	***Biological control*** _Pest regulation _Invasive species resistance _Disease regulation	***Fixation of solar energy*** _Primary production / plant growth *(above/below ground, marine, fresh water)*	*Cultural diversity + heritage* *Natural diversity + heritage*
Raw Materials _Timber _Fiber _Stone _Minerals	***Prevention of disturbance and moderation of extremes*** _Wind/wave force modification _Erosion + landslide control _Mitigation of flood/drought *(groundwater recharge, surface runoff, etc.)* _Other	***Habitat Provision*** _Nest site _Shelter _Food _Safety _Interconnected to other patches _Habitat diversity	*Spiritual and religious inspiration* *Creation of a sense of place* *Relaxation and psychological well-being* *Artistic Inspiration*
Fuel _Biomass _Mineral _Wood _Other	***Climate Regulation*** _Greenhouse gas regulation *(global)* _Ultraviolet light protection _Moderation of temperature _Wind regulation _Rainfall regulation	***Species Maintenance*** _Biodiversity _Natural Selection _Self-organization _Self-sustaining populations	*High Value Workspace** *Foster social connections + communities*** *Physical well-being + healing****
Fresh water _Consumption _Irrigation _Industrial Processes	***Decomposition*** _Waste removal _Waste filtration	***Nutrient cycling*** _Regulation of biogeochemical cycles _Retention of nutrients _Recycling nutrients	
Ornamental Resources	***Pollination and seed dispersal***		
Genetic Information			

TABLE 10.1 Identified ecosystem services that ecosystems can provide (partially adapted from Kandziora (2013), Zari (2011) and Burkhard (2010) charts[70, 238, 486])

*Notes: *Based on research discussed in Chapters 6 and 7*
***Based on the existing research discussed in Chapter 9[487]*
****Based on existing research that has found that natural environments improve physical health and recovery,[147, 274, 327, 353, 442, 451] and reduce toxins in environment, including air, water, and soil pollution,[111, 146, 349, 398] among other benefits. Some of these issues are discussed in more detail in Chapter 9*

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§ 10.2.1.3 Distinguishing between ecosystem functions and services

The distinction between a number of ecosystem functions and services is still unclear. For instance, the classification of a number of individual ecosystem services and functions are still under debate.[71, 74, 189] For example, Boyd (2007) proposed a human benefit based definition method, in which previously defined ecosystem services that do not provide direct benefits to humans, such as nutrient cycling and other supporting services, should be re-classified as ecosystem functions, or in some cases, intermediate services.[60] From this perspective, the provision of flood control functions can only be defined as a service when floods pose a threat to a community.[189]

However, Burkhard (2012) contends that this definition strategy tends to be observer based and subjective, and therefore not effective.[71] As an alternative, Burkhard (2012) proposed that the distinction between ecosystem functions and services should be from an ecological integrity based perspective, in which ecosystem services that promote the ecological integrity of an ecosystem should be defined as ecosystem functions. This strategy effectively reclassifies previously defined supporting services as ecosystem functions. To this end, Burkhard (2012) presents experimental evidence that suggests that the evaluation of several supporting services can be used as a comprehensive evaluation of a natural ecosystem's ecological integrity.[71] However, the results of a number of studies suggest that the specific ecosystem services that are effective indicators of an ecosystem's ecological integrity are context dependent, and thus variable.[71, 238, 486] For instance, Kandziora (2013) found that besides the indicators identified by Burkhard (2012), a number of other ecosystem functions and services were also integral to evaluating the ecological integrity of a terrestrial ecosystem in Germany.[238]

Similarly, the application of both of these ecosystem service and function definition methods indicate that the classification of individual ecological processes and structures as ecosystem services or functions are dependent on the context of the ecosystem under analysis. Furthermore, regardless of these types of debates and other confounding factors, the results of a number of studies demonstrate that the definition of individual ecosystem indicators as services or functions can vary over time, due to the complex interrelationships between ecosystem structures and processes, as well as constructed and natural ecosystems, among other contextual factors. In addition, the definition of ecosystem processes and structures as ecosystem functions or services is inherently influenced by the shifting levels of demand, and value, of the service or function by local and global human communities.[60, 189, 238] Therefore, further research is needed to determine effective ecological integrity indicators for various types of natural and constructed ecosystems, as well as factors that substantially influence the ecological integrity of various types of ecosystems. These issues will be discussed in more detail in Sections 10.2.2, 10.2.4, and 10.4.

Moreover, as discussed in Sections 10.2.2.8 and 10.2.4, ecosystem functions and services that have been identified in existing literature, as shown in Table 10.1, can be used to assess potential ways constructed environments and ecosystems can improve local and global ecosystems. Therefore, in terms of design for ecological performance, it is more important for design teams to determine the relative influence of ecosystem services and functions on the functions and integrity of local ecosystems, than to determine whether individual ecological processes and structures are ecosystem functions or services.

§ 10.2.2 Assessing the value and priority of individual ecosystem services

Similar to the issues of defining ecosystem services discussed in Section 10.2.1.3, the accurate assessment and value of ecosystem functions and services are dependent on a number of dynamic typological, contextual, social, spatial, scalar, and temporal issues. Furthermore, due to these variable issues, among other factors, the value of individual ecosystem functions and services are inherently dynamic. The following subsections discuss the relevance of these issues in assessing the value of individual ecosystem services and functions.

§ 10.2.2.1 Typological valuation issues

In general, different types of ecosystems have different functions and services, based on their inherent structures, processes, and species richness and types, among other influential factors. Thus, it may be possible to develop an assessment tool that evaluates the ecosystem functions and services that are provided by different types of ecosystems.

This type of assessment tool can be helpful for design teams to account for the functions and services of local ecosystems in their design solutions. For instance, Burkhard (2012) proposed an assessment of the capacities of different ecosystem types to support their ecological integrity and provide ecosystem services. However, this assessment was based on the results of a limited range of existing case studies, which were dependent on the various researchers' personal observations, knowledge, objectivity, and non-uniform assessment methods.[35, 71] Thus, further research is necessary to develop a more accurate and comprehensive ecosystem type assessment tool.

Furthermore, it is important to note that the value of the functions and services of ecosystems, even of similar ecosystem types, vary based on a number of dynamic and contextual factors, as will be discussed in the following subsections. Thus, this type of generalized, comparative ecosystem assessment tool can be helpful for distinguishing the general ecological performance of the services and functions of different ecosystem types. However, this type of assessment tool is inherently limited in terms of providing comprehensive, precise assessments of individual ecosystems.

§ 10.2.2.2 Contextual valuation issues

The value and priority of ecological integrity and ecosystem service indicators of the same types of ecosystems, as well as different ecosystem types, vary based on their context. For instance, although ecosystem services have been categorized into individual services and functions, they are inherently interrelated. In fact, some researchers have suggested that it may be impossible to categorize some services into independent conditions and processes for evaluation.[84] Furthermore, different ecosystems inherently provide different quantities, qualities, and types of ecosystem functions and services.[71] Moreover, the ecological functions, integrity, and services of individual ecosystems are directly impacted by the inherent and dynamic interrelationships between the individual local ecosystems within the region, as discussed in Chapter 8. Thus, the ability of individual ecosystems to supply particular ecosystem services varies substantially, and is dependent on the context of the ecosystem, such as the state of the other local ecosystems.[325]

§ 10.2.2.3 Spatial valuation issues

The spatial characteristics and geographic location of an ecosystem substantially influences its ecological integrity and ecosystem services, and therefore are important to assess.[35] Thus, the spatial visualization and assessment of ecosystem services provides essential insights into the performance and quality of an ecosystem, as well as individual services and functions.[71, 176] These issues are discussed in more detail within the context of an urban core ecosystem in Section 10.4.

§ 10.2.2.4 Temporal valuation issues

The provision and value of ecosystem services are invariably dynamic due to the constant flux of an ecosystem's state and properties, among other factors. Thus, the value of ecosystem functions and services vary over time, both due to natural and human influences.[71] For example, the state of an ecosystem can be substantially altered by natural disturbances, such as flooding. Furthermore, the value of ecosystem services can vary considerably, based on the level of demand of the particular service by the community of interest at the time of evaluation, as discussed in Section 10.2.1.3.[189] Moreover, the consumption and accumulation of resources within urban areas typically increases over time, which inevitably affects local and global ecosystems, and thus is important to consider.[216, 248, 325]

§ 10.2.2.5 Social valuation issues

The value of ecosystem services is dependent on the demand and/or need (value) of the service by local and global human communities.[60, 71] Thus, several researchers have suggested that ecosystem functions, such as flood control, should only be considered to be ecosystem services when they benefit a community, as discussed in Section 10.2.1.3.[189] In turn, the probability of a natural ecosystem being disturbed or directly destroyed by people depends in part on the value they place on the ecosystem, its functions and services, and the possibility and ease that urban areas can fulfill their resource demand in another manner.

§ 10.2.2.6 Scalar valuation issues

The evaluation of ecosystem services at the individual city, building, and natural ecosystem scale, compared to regional and global scales, have received much less research attention, and present a number of challenges that have yet to be resolved.[71, 88, 325] For instance, building scale assessments require more accurate data than city and regional evaluations, because the sensitivity of calculations to the impreciseness of data increases at the building scale. At the same time, a relatively low amount of ecological data is typically available at the scale of buildings and individual ecosystems.[74] Furthermore, as discussed in Chapter 8, it is important to consider that assessments conducted at the individual ecosystem scale typically lead to overestimations of ecosystem services. Moreover, they diminish the influence of the interrelationships of individual ecosystems, as well as ecosystem and regional scale factors, such as the spatial interrelationships of different ecosystems, on overall ecosystem services.[157] A review of these challenges is outside the scope of this chapter. Moore (2013) and Chapter 8 discuss these issues in more detail.

§ 10.2.2.7 General valuation issues

It is important to note that the full value of a number of individual services have not yet been determined, such as the impact of the cultural and social value of ecosystem services on their valuation.[83, 84, 238] For instance, although cultural services are typically valued less than other services, the provision of cultural services can promote ecological awareness and behavior, which can contribute to improving the functions of local and global ecosystems.[71, 238] This is discussed in more detail in the Chapter 9. Furthermore, individual ecosystem services and functions are inherently interrelated in a myriad of ways, as discussed in Section 10.2.2.2. Due to these issues, among others, researchers often find it difficult to eliminate the double counting of overlapping benefits, as well as to accurately distinguish the absolute and relative value of individual ecosystem services.[84, 238] Further research is necessary to develop a more detailed and accurate valuation system.

§ 10.2.2.8 Comprehensive evaluation of the integrity of individual ecosystems issues

Therefore, in order to account for these influential factors, such as the contextual nature and inherent interrelationships of ecosystem services and functions, as well as to evaluate the integrity of ecosystems, it is necessary to evaluate the ecosystem services and functions of an ecosystem comprehensively, rather than individually. However, it is important to note that an effective, comprehensive ranking and valuation system of ecosystem functions and services, based on their importance to the ecological integrity and/or functions of an ecosystem, has not yet been developed.[71, 189, 486] For instance, various studies have found conflicting functions and services to be important to promoting the ecological integrity of ecosystems, as discussed in Sections 10.2.1.3, 10.2.4, and 10.2.5. For example, a number of studies have identified biodiversity as an important ecosystem function to promote the ecological integrity of ecosystems, as discussed in Section 10.2.5, while other studies have found other factors, such as habitat diversity, a supporting service, and resilience, which can be determined by evaluating a number of ecosystem functions, to be equally or more important.[71, 396] Furthermore, as discussed in Sections 10.2.4 and 10.4.9, the relative value of various functions has been found to be context dependent, and a diverse range of functions and services within each of the four ecosystem service categories have been found to be important to promote the integrity of an ecosystem, depending on the context.[20, 238, 402]

Moreover, the results of a number of investigations indicate that the development of such an evaluation system may not be possible. For instance, there are currently a number of limitations to such an evaluation system. There are significant knowledge gaps about ecosystems, and natural ecosystems have numerous non-linear complexities that have yet to be synthesized, due in part to their dynamic spatial and temporal characteristics and interrelationships. In addition, the benefits of natural ecosystems are difficult to codify. They provide direct and indirect benefits, as well as benefits that are difficult to quantify.[71, 83, 84, 189, 238]

Nevertheless, a number of general ecosystem service categorization and assessment methods have been developed, and are discussed in Sections 10.2.3 and 10.2.4. Furthermore, Section 10.3.1 discusses existing constructed ecosystem function assessment methods, as well as existing limitations to comprehensively evaluating the ecosystem functions and services of urban core ecosystems. Similar to the discussion in Chapter 8, it is important to assess the ecological integrity and ecosystem functions of local natural ecosystems when determining the potential of building projects within the context of urban core ecosystems to promote ecosystem functions. To this end, a number of natural ecosystem ecological integrity assessment methods have been developed, but a review of these methods is outside the scope of this chapter.[184, 481]

§ 10.2.2.9 Value of addressing individual ecosystem services and functions during the design process of constructed environments

Regardless of these limitations, it is important to note that the identification, development, and evaluation of a list of individual ecosystem services and functions can serve as guidelines, as well as part of ecological design support systems, for design teams to determine which strategies, and ecosystem services and functions, are most appropriate to address within a project's context.[71, 88, 176] For instance, as discussed in Section 10.2.1, ecosystem services that have been identified in existing literature, such as those listed in Table 10.1, can provide a limited overview of the potential functions and services of an ecosystem that can be addressed by buildings and constructed ecosystems.[238] Furthermore, several existing and potential methods to integrate ecosystem functions and services into an urban ecological design support system are discussed in more detail in Section 10.3.2.

§ 10.2.3 Defining ecosystem service categories

Although the ecosystem services listed in Table 10.1 are organized into four ecosystem service categories, it is important to note that a clear consensus of ecosystem service categories has not yet been achieved, similar to the discussion in Section 10.2.1.3. Furthermore, new categorization methods are continuously under development, and it may be that the determination of the appropriate categorization method for a specific project depends on the project's context and application goals.[104, 238, 465] For instance, several researchers have proposed that regulating and supporting services should be combined, partly because they provide less tangible, more indirect benefits to humans.[60, 465] However, as previously discussed in Section 10.2.1.3, the distinction between direct and indirect services is subjective and still unclear.[71] A review of the various ecosystem service categorization methods that have been proposed in existing literature is outside the scope of this chapter. Haines -Young (2010) provides a review of existing literature on this topic.[189] Nevertheless, from a design perspective that is focused on improving the ecosystem functions of local ecosystems, the distinction between, and inclusion of, regulating, provisioning, supporting, and cultural services are useful for considering the potential ecosystem functions and services that can be addressed by various design solutions, as well as identifying effective design strategies and solutions.[455, 486]

§ 10.2.4 Assessing the value + priority of ecosystem functions according to ecosystem service categories

A number of categorical ecosystem function and service assessment methods have been proposed and evaluated in existing literature. Results from these studies have found that different categories of ecosystem services can have different impacts on an ecosystem's integrity, functions, and services.

For instance, Zari (2012) evaluated several individual ecosystem services in terms of their importance to promoting ecosystem functions, based on criteria developed from a literature review. Ecological services were rated on a three point scale: low, medium, and high. However, every service was found to be of high value, except for some of the provisioning services. Zari (2012) suggested that some of the provisioning services can be less important because they mostly benefit humans, and are not as important in maintaining the ecological integrity of natural ecosystems.[486] In addition, Burkhard (2012) found experimental evidence that the evaluation of several supporting services could effectively evaluate the ecological integrity of a natural ecosystem, as discussed in Section 10.2.1.3.[71] This finding suggests that supporting services are more important to maintain the functions and ecological integrity of a natural ecosystem than other categories of ecosystem services.

However, a number of other studies have found that ecosystem services within every category can be important to the integrity of an ecosystem, and thus are important to evaluate. For instance, existing research suggests that the relative abundance and diversity of functions within an ecosystem are key to maintaining the ecological integrity and functions of ecosystems.[20] Moreover, there is evidence that a decline in one service impacts the performance of other ecosystem services, and that each of the four ecosystem service categories can provide valuable ecosystem services, in terms of promoting the integrity and functions of an ecosystem.[238, 402] For example, Kandziora (2013) evaluated the categorization method proposed by Burkhard (2012) for an agricultural ecosystem in Germany, and found that other ecosystem functions and services, particularly a number of regulating services, but also several provisioning and cultural services, were also important in evaluating the ecological integrity of the ecosystem.[238] Nevertheless, regulating and supporting services were generally more important to maintaining the ecological integrity of the agricultural ecosystem than provisioning and cultural services.[238] However, it is important to note that due to current limitations in valuing individual ecosystem services, particularly cultural ecosystem services, as discussed in Section 10.2.2, the value of the various services was not fully accounted for in existing studies.

These findings, among others, suggest that the general individual functions of an ecosystem are accounted for within the four ecosystem service categories discussed in Section 10.2.1.1, particularly within the supporting services category, and to a lesser extent, the regulating services category. Moreover, individual ecosystem services within all four ecosystem service categories can be important contributors to an ecosystem's ecological integrity, and thus are important for assessing, and designing constructed environments to promote, the ecological integrity and functions of ecosystems.

Furthermore, the different values found for individual and categorical ecosystem services within existing literature, in terms of promoting the integrity and functions of ecosystems, suggests that the relative value of different categories of ecosystem services are context dependent. This finding is also in agreement with the literature previously discussed in Sections 10.2.1.3 and 10.2.2.2.

Moreover, the relative value of ecosystem services in some ecosystem service categories have been found to be more difficult to accurately assess than services within other service categories. For instance, a number of regulating services relate to both ecological processes and ecosystem services, and are therefore often double counted in ecological integrity and ecosystem service assessments.[71] Furthermore, regulating, supporting, and cultural services provide less tangible benefits than provisioning services. Due to this inherent quality of regulating, supporting, and cultural services, they are not widely acknowledged by individuals and communities, and they are more difficult to quantify than provisioning services. Indeed, provisioning services have been integrated into economic models and systems for a longer period of time.[71, 238]

§ 10.2.5 Assessing the value of biodiversity, in terms of its potential contribution to (other) ecosystem functions

The interrelationships between ecosystem services and biodiversity have not yet been clearly defined.[28, 35] Indeed, Bastian (2013) went so far as to suggest that the specific nature of the interrelationships between biodiversity and ecosystem functions is 'one of the most important unresolved questions in ecology.'[35]

Nevertheless, existing studies have found evidence that natural ecosystems require a stable state of biodiversity to maintain a number of ecosystem services and functions, and that the state of an ecosystem's biodiversity and functions substantially affect each other.[103, 219, 238] For instance, Isbell (2011) found that the type of plant species that provided individual ecosystem functions within a specific location varied from year to year, in regards to a range of functions and locations. Moreover, the findings indicated that more species are needed to maintain ecosystem functions and services than have been found in previous studies that didn't account for multiple influential factors, including different times (in years), places, functions, and environmental changes.[219] These findings suggest that many species are necessary to maintain multiple functions at multiple locations. Furthermore, although some species may seem functionally redundant, and therefore unnecessary in terms of providing ecosystem functions, they can be necessary, and not redundant, when taking into account the dynamic factors of a site and multiple ecosystem functions.[219] In addition, Costanza (2007) calculated that a 1.0% increase in biodiversity results in a 0.5% increase in overall ecosystem services in warm ecoregions. However, in other ecoregions, biodiversity was not found to significantly influence ecosystem services. To this end, Costanza (2007) calculated that other ecoregions only provide 30% of the world's ecosystem services, which may help explain the insignificant effect of biodiversity on the services of ecosystems in these regions. These type of findings have led some researchers to suggest that biodiversity should be prioritized and given a greater value than other ecosystem functions.[103]

However, a number of existing studies have found poor correlations between biodiversity and ecosystem functions.[28, 35, 396] Moreover, a review of existing research by Schwartz (2000) found that there was not a direct relationship between biodiversity and a number of ecosystem functions, and that several other ecosystem properties, such as resilience and habitat diversity, were equally as important as biodiversity to provide ecosystem services and sustain a range of ecosystem functions.[396] Moreover, Bastian (2013) found, through both literature review and experimentation, that the provision of a number of ecosystem services were not dependent on a particular species. In addition, the contribution of biodiversity to specific ecosystem functions varied by ecosystem service category and specific ecosystem functions. For example, cultural services were found to be the most dependent on the presence of specific species, species groups, and habitat types, as well as some regulating services. In contrast, a number of other services, particularly provisioning services as well as a number of regulating services, were more dependent on vegetation structures and land cover.[35] Furthermore, a number of researchers have suggested that there are still significant knowledge gaps, as well as a lack of evidence, to effectively evaluate the interrelationships between biodiversity, ecosystem functions, and ecosystem services.[35, 117, 317, 396] These findings, among others, suggest that biodiversity should not be valued more than other ecosystem functions.

Regardless of these issues and the need for further research, extant research indicates that in general, the more ecosystem functions that are provided, the more species diversity is necessary to sustain the functions of an ecosystem.[202, 393, 455] Furthermore, a number of studies have found that the improvement of an ecosystem's biodiversity typically results in the provision of additional ecosystem services.[103, 455] In addition, the resilience of natural ecosystems depends on the distribution, abundance, and dynamic interactions of species, at multiple spatial and temporal scales. To this end, natural ecosystems with high species function diversity have been found to have greater resiliency.[455] Moreover, there is evidence that all components of biodiversity may play a role in the long-term supply of at least some ecosystem services. Thus, the maintenance of the quality and quantity of biodiversity attributes may result in a diverse, rich flow of ecosystem functions and services within natural ecosystems.[183, 219] However, further research is necessary to determine the interrelationships and relative value of biodiversity and ecosystem functions in supporting the functions and integrity of ecosystems.

Moreover, in terms of the potential effectiveness of the design of a building project to improve the biodiversity of local ecosystems, in order to improve the quality and quantity of the ecosystem functions and services of the local ecosystems, it remains unclear if the improvement of the biodiversity of a constructed or natural ecosystem is an effective method to improve the functions and services of the ecosystem. Thus, addressing ecosystem functions and services through design for biodiversity may be ineffective.

Furthermore, similar to the literature findings discussed in Sections 10.2.2 and 10.2.4, extant literature suggests that the value of biodiversity to promote an ecosystem's integrity, functions, and services depends on the context of the building project.[103, 202, 396] In addition, similar to the study by Isbell (2011), Bastian (2013) found that the evaluation of the state of the functions and integrity of an ecosystem through the evaluation of the state of specific species that have been found to maintain specific ecosystem functions and services in existing literature is ineffective, as these species have diverse interactions with other species and processes that are currently too complex to comprehensively observe and evaluate. Hence, the determination of the species that are necessary to produce specific ecosystem services within a building project's ecosystem may not be possible, nor may it be possible to predict the effects of the loss of a single species, population, or ecosystem service or function.[35, 219] These issues are further discussed in Section 10.4.9. Thus, the results of existing literature indicate that design solutions need to address a number of biodiversity and ecosystem function and service performance parameters, in order to effectively improve the state of the ecosystem functions of the local ecosystems.

§ 10.2.5.1 Assessing the value of addressing biodiversity within an urban context

Furthermore, it is important to note that the interrelationships between biodiversity and the functions and services of constructed ecosystems may be substantially different, and less interdependent, than within natural ecosystems. These issues are discussed in more detail in Sections 10.3.1 and 10.4. In addition, similar to the discussion in Section 10.3, the inherently different state of biodiversity within typical constructed ecosystems, as well as the interrelationships between biodiversity and ecosystem functions, is not yet well understood and requires further research. The current lack of research makes the assessment of the value, interrelationships, and potential effectiveness of promoting biodiversity within the context of a constructed ecosystem, with the goal of improving the functions and services of the local ecosystems, exceptionally challenging.

For instance, the effectiveness of addressing biodiversity within constructed ecosystems, particularly in regards to the potential for positively contributing to regional biodiversity conservation efforts, is currently under debate,[28, 257, 281] and is inherently dependent on the context of a project, among other factors, as discussed in Section 10.2.2, 10.4, and Chapter 11. For example, constructed environments within urban core ecosystems may provide unique opportunities to facilitate biodiversity

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through access to diverse resources and technical infrastructure systems, as discussed in Section 10.4 and Chapter 11.

In contrast, provisions for biodiversity may have adverse effects on different functions and services within constructed ecosystems. Moreover, the typical use of technical infrastructure systems, as opposed to natural systems and processes, within constructed ecosystems may reduce their reliance on biodiversity. Thus, functions within constructed ecosystems may benefit less from biodiversity than similar functions within natural ecosystems. These issues are discussed in more detail in Section 10.4. Furthermore, the potential benefits, opportunities, and issues of addressing biodiversity within constructed ecosystems are discussed in more detail in Chapter 11.

§ 10.3 Assessing the potential of constructed environments to promote the functions of local ecosystems

Due to the scalar issues discussed in Chapter 8, in terms of designing constructed environments to improve the functions of the local ecosystems, building scale design solutions should be focused on addressing the ecosystem functions that are most important to address at the larger regional scale. This requires an evaluation of the ecosystem functions of the local constructed and natural ecosystems within the region. However, it is important to note that there are a number of issues that influence the potential of building scale design solutions to contribute to specific ecosystem functions. Furthermore, as previously discussed in Section 10.2 and Chapter 8, there are also a number of existing limitations with assessing the functions of the ecosystems within a region.

A review of the various assessment methods and existing results for evaluating the functions and integrity of a range of natural ecosystems is outside the scope of this book. Nevertheless, Section 10.2.2 discusses existing general issues with assessing individual ecosystem functions and developing comprehensive natural ecosystem assessment methods, and Section 10.2.4 discusses several categorical ecosystem assessment methods. Furthermore, this section discusses several existing and potential constructed ecosystem function assessment methods, a range of factors that influence the functions of constructed ecosystems, existing research gaps, and the effectiveness of various existing and potential ecological design strategies to improve the functions of local ecosystems.

§ 10.3.1 Assessing the value + priority of constructed ecosystem functions

An assessment of the functions of the local constructed and natural ecosystems allows for the identification of the ecosystem functions that are most important to address within the region, as well as potential high impact opportunities for constructed environments to contribute to the improvement of the functions of local ecosystems. For instance, regional and ecosystem scale ecosystem function analysis can help identify potential locations where design interventions can be developed to have a relatively high impact on the functions of local and global ecosystems.[248]

In addition, comparative analyses of ecosystems can be useful in identifying important typical and ecosystem specific local and global ecosystem function issues. For instance, a comparative analysis of the water consumption footprints of US cities (urban areas) found that unintended water losses made up a substantial portion of most of the cities' water consumption footprints, which indicates that this issue is typical for constructed ecosystems that are situated within urban areas, at least within the context of the US.[30]

However, as discussed in Section 10.2, a standardized ecosystem function valuation method has not been developed for natural ecosystems. Similarly, a standardized method to comprehensively evaluate the functions of constructed ecosystems has not yet been developed. Moreover, data from individual studies typically are derived from different assessment methods, and therefore are not readily comparable.[35]

Furthermore, it is important to note that extant research indicates that the state and functions of typical constructed ecosystems are markedly different than natural ecosystems, and therefore likely require different assessment methods. For instance, since urban core ecosystems are typically low in ecosystem services, functions, and biodiversity, as discussed in Chapter 8, the potential value of various individual and categorical ecosystem functions and services are typically different, and more volatile, than within the context of natural ecosystems.[175] Moreover, the effects of the state of biodiversity of an ecosystem on its functions may be less valuable within urban core ecosystems, as discussed in Section 10.2.5.

Thus, further research is necessary to assess the functions of constructed ecosystems. Nevertheless existing research can provide some insight into the assessment of the functions of constructed ecosystems. Therefore, the following subsections review existing research on the state and functions of urban core ecosystems, factors that affect the evaluation of the functions of urban core ecosystems, as well as several existing and proposed methods to assess the functions of urban core ecosystems.

§ 10.3.1.1 Current limitations of assessing the functions of urban core ecosystems

A number of factors limit the effective assessment of the functions of urban core ecosystems. For instance, urban core ecosystems are typically close to passing ecological thresholds, due to their low ecosystem services, functions, and biodiversity, among other factors. Ecosystems that are close to ecological thresholds are more unstable. This instability increases the possibility of abrupt shifts in an ecosystem's supply of services, and makes them more susceptible to disturbances. Moreover, the value, quality, and quantity of their ecosystem services can change quickly, drastically, and in non-linear ways, sometimes irreparably. Furthermore, multiple stressors within urban core ecosystems make it difficult to identify the underlying cause of various disturbances and negative influences on ecosystem functions, thereby making it difficult to assess the most important ecosystem functions that should be addressed to improve the state of urban core ecosystems.[175] In addition, the limiting factors of assessing the functions of natural ecosystems that were discussed in Section 10.2.2, such as scalar, temporal, spatial, and contextual issues, are relevant to urban core ecosystems as well. These factors, among others, such as the highly heterogeneous nature of urban areas, make it difficult to accurately assess the value of the functions of urban core ecosystems.[464]

Despite these issues, and the relative importance of the functions of urban core ecosystems to local and global ecosystems, as discussed in Section 10.1.2 and Chapter 8, the assessment of the performance of the functions and state of urban core ecosystems is currently receiving relatively scant research attention, compared to natural ecosystems.[183, 259]

§ 10.3.1.2 Identifying common urban core ecosystem functions

Nevertheless, some general conditions of typical urban core ecosystems have been identified in existing research. For example, urban core ecosystems tend to be distinct from natural ecosystems in regards to a diverse range of performance parameters. For instance, urban core ecosystems tend to have large quantities of imported resources, infrastructure, and technology, as well as provide opportunities to influence the behavior of relatively large human populations. These parameters provide both unique opportunities and limitations, such as opportunities to develop technologies and infrastructure systems that generate ecosystem services and functions, which is further discussed in Section 10.4.[9, 425] Furthermore, the state of typical urban core ecosystems is discussed in more detail in Chapter 8, including the potential of design to improve the ecological integrity of urban core ecosystems.

§ 10.3.1.3 Identifying + assessing existing urban core ecosystem services + functions assessment methods

In order to accurately assess the state of urban core ecosystems, further research into the value of individual and categorical ecosystem services within urban core ecosystems is necessary. Furthermore, as discussed in Sections 10.2.2 and 10.3.1, a standardized, validated ecosystem function assessment method has not been developed for natural or constructed ecosystems.[35, 88, 176] Nevertheless, a number of urban core ecosystem function assessment methods have been developed and proposed. Although a comprehensive review of existing urban core ecosystem function assessment methods is outside the scope of this chapter, several proposed and applied assessment methods are reviewed in the following subsections.

Natural Ecosystem Reference Method

Zari (2012) suggested that the performance of the functions of constructed ecosystems, and potential design solutions, can be evaluated by being compared to the performance of the ecosystem functions of existing local natural ecosystems. If none exist, the performance of the site should be compared to the natural ecosystem that existed on the site before the constructed ecosystem was developed.[486]

This assessment method has a number of limitations. For instance, as discussed in Section 10.2.2, the functions and state of an ecosystem fluctuate over time. These variations can make the use of past local ecosystems an unsuitable model in some contexts.[467] In addition, the functions of similar ecosystems can vary considerably, and the performance potential of an ecosystem partially depends on its connectivity and interrelationships with local ecosystems and other contextual factors. These issues make comparisons between ecosystems difficult.

Resource Demand Analysis Methods

An existing alternative approach to assess the functions of urban core ecosystems is to analyze the effects of an urban core ecosystems' resource demand. Several urban core ecosystem resource demand analysis methods have been developed and assessed, including urban metabolism and ecological footprint analyses.

Urban core ecosystem service footprint and ecological footprint analyses provide a method to compare the available supply of natural resources in local and global ecosystems to the demand of resources by people, by estimating the quantity of natural ecosystem area that is necessary to sustain an urban core ecosystem's resource demand, as discussed in Section 10.1.1.[71]

Urban metabolism analysis is a similar methodology, in that it is a method that is in principal intended to account for the inputs, outputs, and storage of energy, water, pollutants, nutrients, materials, and waste within an urban core ecosystem. These studies also attempt to evaluate the socio-economic processes that affect the process flows within an urban core ecosystem.[248] However, most existing studies have focused on one or two individual performance indicators, instead of a comprehensive model. [88, 169, 325]

Assessing the value of existing urban core ecosystem assessment methods

Similar to the discussion in Section 10.3.1, existing studies that use either one of these assessment methods typically employ different assessment methodologies, which tends to render incomparable results. Moreover, these analyses are largely focused on evaluating the quantifiable resources within urban core ecosystems, and thereby do not comprehensively evaluate the diverse functions of urban core ecosystems, nor the functions of the local ecosystems within the region. In addition, resource processes that occur within the city, such as their transformation, accumulation, and consumption, are typically not evaluated in these studies. This makes the development and assessment of solutions to an urban core ecosystem's resource issues problematic.[216] Thus, further research is necessary to develop more comprehensive urban ecosystem function assessment methods.[71, 88, 176, 248, 325]

Nevertheless, existing studies within these research domains provide some insight into the functions of urban core ecosystems. Furthermore, despite their limitations, the results from the application of these urban ecosystem function assessment methods highlight the importance of taking into account regional, and ecosystem specific, influential factors. For instance, the general results from the resource demand analysis methods indicate that different cities have substantially different ecological footprints and resource consumption.[169, 225, 248, 325] For example, the topography and water availability in Vancouver has a substantial influence on the ecological footprint of Vancouver's water consumption.[325] These findings reinforce the importance of the specific context of individual urban core ecosystems on their functions, the importance of accounting for contextual factors when comparing multiple ecosystems, as well as the importance of assessing urban core ecosystems on a case by case basis.

§ 10.3.2 Exploring methods to assess the potential of constructed environments to contribute to the functions of local and global ecosystems

When assessing the potential of constructed environments to contribute to the functions of local and global ecosystems, both during design and operation stages, it is important to assess the state of the functions of the project site, as well as the potential effects of the design solution on the functions of local and global ecosystems. However, similar to the discussions in Sections 10.2.2 and 10.3.1, the calculation of the performance and value of individual ecosystem functions at the building scale, including avoiding overlaps, is difficult.[74]

Similarly, it is important to note that it can be particularly difficult to assess the performance potential of a building and building site. For instance, it can be difficult to evaluate the vegetation growth and biomass potential of a building site. Modern growing techniques, including green walls, hydroponics, and aquaculture, as well as building design strategies, such as the use of terracing techniques to maximize vegetation growth area, can provide extensive plant growth opportunities, potentially even more than local natural ecosystems.

Furthermore, similar to the discussion in Section 10.3.1, the ecological value of design solutions within urban core ecosystems can be substantially different than for analogous design solutions within the context of more natural ecosystems. For example, the effects of interior gardens on nutrient cycling and habitat provision are generally substantially limited, although the effects vary based on growth method, location, and the type of design solution, among other factors. Thus, the effectiveness of the provision of various ecological processes and biota within constructed environments are necessary to be assessed, but at the same time, pose a number of challenges. These issues are discussed in more detail in Section 10.4.

Moreover, some ecosystem functions are exceptionally difficult to assess at the design stage, before they are implemented, due to a lack of existing information about the site and the ecological value of various design solutions, among other factors. Furthermore, as discussed in Section 10.2.4, some ecosystem services and functions, such as provisioning services, are more easily accountable than others.

Nevertheless, even rough calculations of ecosystem functions can provide performance indicators for design teams to use when assessing the performance of various design solutions, as well as the performance of the existing building site. Several preliminary building scale ecosystem function assessment methods have been developed and proposed, and are reviewed in the following subsections.

§ 10.3.2.1 Urban metabolism assessment methodology

The European F7 project BRIDGE incorporated an urban metabolism assessment methodology that allowed for the evaluation of the impact of various design solutions on the current and potential future state of the constructed ecosystem the building project was sited within. This methodology resulted in the development of a design support system (DSS) for local municipalities and planners.[176] The BRIDGE DSS was used to evaluate material, energy, water, waste, carbon, pollution, social, and economic performance indicators of various design solutions, through both top down and bottom up assessment methods. However, the BRIDGE DSS had a number of limitations. For instance, it did not take into account certain adjacency factors at the building scale, such as the influence of the geometry of building integrated habitat patches on biodiversity. In addition, the BRIDGE DSS did not account for less quantifiable ecosystem functions and services, and therefore, was not a comprehensive ecosystem function evaluation tool. The BRIDGE DSS also did not assess the functions of local natural ecosystems, nor the influence of design solutions on the functions of these ecosystems.[88] Nevertheless, this model can provide a limited assessment of the comparative impact of varying design solutions on the constructed ecosystem building projects are sited within, and can aid in the evaluation and identification of locally important ecosystem functions. Moreover, the BRIDGE DSS method can be combined with other assessment methods to generate a more comprehensive understanding of local constructed and natural ecosystems, as well as the impacts of various design solutions.

§ 10.3.2.2 Natural ecosystem function performance reference assessment methodology

The Zari (2012) ecosystem comparison method can be applied at the building scale, by calculating the proportion of the various ecosystem functions of a local natural ecosystem, or of the natural ecosystem that previously inhabited the building site, that can be provided by the building site. These calculations should be based on the ratio, (A/E), of the project site area (A) in relation to the total area of the ecosystem (E). For example, applying the method of Zari (2012) to a building's carbon sequestration rate suggests that sequestering as much carbon as the original ecosystem provided, for the area of the site, is an optimal ecological performance goal.[486]

However, this assessment method has a number of limitations, similar to the issues discussed in Section 10.2.2. For instance, the assessment of functions that are not easily quantified is problematic. Furthermore, similar to the discussion in Sections 10.2.2, 10.3.1, and 10.4, the performance of various ecosystem functions within building and ecosystem scale areas of natural ecosystems is considerably variable, contextual, and difficult to assess accurately.[74, 157] In some cases, specific ecosystem functions that are important for urban areas to address may not have been provided by local ecosystems. Furthermore, as discussed in Section 10.1.2, the demands of individuals, buildings, and cities on the functions and services of local and global ecosystems are considerably greater than these ecosystems can provide.[57, 150, 377] Thus, depending on the building design, occupancy rate, and building area to site area ratio, among other factors, the provision of ecosystem services and functions by the original natural ecosystem, in proportion to the area of the building site, may not be able to support the needs of the building and its inhabitants. This issue also applies to the urban core ecosystem scale. Thus, the natural ecosystem target goal can be insufficient to address the influence of buildings and cities on the functions of local and global ecosystems, and therefore may not be an appropriate goal. Nevertheless, the Zari(2012) method can be employed as a rough assessment method to comparatively evaluate the ecological performance and potential of building design solutions.

§ 10.3.2.3 Maximum ecosystem function performance potential assessment methodology

Alternatively, the comparison of a building's ecological performance to the maximum positive performance potential of each ecosystem function within the context of the building site, may be a more effective method to evaluate the relative performance of individual ecosystem functions within a building site. In this approach, the maximum performance limit for specific ecosystem services would remain undefined. For example, the site carbon sequestration goal described in Section 10.3.2.2, would be redefined, according to this alternative method, to absorb as much carbon as possible for a given site.

This type of performance goal would thus be defined in a manner that encourages design teams to continually question the definition of the maximum performance potential for a given ecosystem service, thereby promoting the continual exploration and development of increasingly effective strategies and design solutions. Furthermore, this type of maximum performance goal has the potential to have a greater impact on the ecosystem functions of local and global ecosystems than the goal proposed by Zari (2012), and can avoid some of the inherent calculation issues discussed in Section 10.3.2.2. For instance, if the carbon sequestration goal of the site was set to the previous carbon sequestration rate of the site when it was part of a natural ecosystem, that type of goal may result in less carbon sequestration at the building site than if the carbon sequestration goal was to sequester as much carbon as possible on the building site. Furthermore, since the goal is not to achieve the same rate of carbon sequestration as the local or original natural ecosystem, the level of accuracy of the natural ecosystem's carbon sequestration rate is not as significant to the design and performance evaluation processes. Regardless of these issues, the pre-existing ecosystem performance comparison method proposed by Zari (2012) can be helpful as a performance baseline. However, it is important to note that the calculation of this baseline may be difficult in some cases, as discussed in Section 10.3.2.2. Thus, by considering the maximum performance potential of a site or design solution as open ended, some of these assessment issues can be avoided.

§ 10.3.2.4 Assessing the effectiveness of existing potential constructed environment assessment methodologies

The assessment methods described in Sections 10.3.2.2 and 10.3.2.3 are both focused on evaluating the performance potential of the project site. In contrast, the BRIDGE DSS assessment methodology described in Section 10.3.2.1 is focused on assessing the performance of the functions of the local urban core ecosystem, as well as the effects of various building design solutions on the performance of several of the ecosystem's functions.

These methods can be complementary. For instance, the site specific assessment methods would require a larger ecosystem scale assessment methodology to identify the ecosystem functions that are most important to address within the building project. As discussed in Section 10.3.2.1, the BRIDGE DSS assessment method can help in this endeavor. On the other hand, different ecosystems have different ecosystem functions, and the value and quantity of different functions varies by ecosystem, based on a number of contextual, temporal, and spatial factors, as discussed in Section 10.2.2. Thus, the identification of the ecological functions of local and pre-existing natural ecosystems, such as proposed in the assessment methods described in Sections 10.3.2.2 and 10.3.2.3, can help identify relevant ecosystem functions, particularly those that are less quantifiable, and perhaps less obvious. Moreover, building scale assessments can help identify and assess building scale ecological design issues, such as the influence of the geometry of the building on local ecosystem functions. Moreover, building scale assessments can aid in the identification and assessment of potential design opportunities and interconnections with the local context that may not be discernable from an ecosystem scale analysis, such as potential interrelationships between the building site and an adjacent habitat patch or aerial corridor.

Thus, although a comprehensive method to assess the effects of individual buildings on local and global ecosystems has not yet been developed, there are existing methodologies that can aid in their development, as well as the ecological design of constructed environments.

§ 10.3.2.5 Identifying general constructed environment design strategies that improve the functions of local + global ecosystems

A number of general building design strategies that address the functions of local and global ecosystems have been incorporated into existing constructed environments. An overview of these strategies, and their relative effectiveness, are discussed in the following subsection.

For instance, addressing provisioning services at the building scale is more common than addressing other types of ecosystem services. This is partially because they are more tangible, quantifiable, and identifiable, are more easily addressed within current design methodologies and solutions, and have a monetary value within current economic systems.[35, 71, 176, 486] To this end, building material and system specifications, as well as the design of the building, can be developed to minimize the initial and operating provisioning service demand of a building, as well as generate provisioning services. For instance, the incorporation of climate responsive design strategies into the design process can reduce the energy demand of the building, as well as provide site rainwater storage and irrigation.

Design strategies that address provisioning services improve the ecosystem functions of local and global ecosystems, by reducing the demand of human communities on natural resources and ecosystems, as well as by directly and indirectly contributing to several regulating and supporting services, such as climate and air pollution regulation.

A related ecological design strategy is to design buildings to reduce the ecosystem service footprints of buildings and their occupants. These strategies are similar to provisioning services design strategies, in that they directly address provisioning services, such as energy and water consumption and production, but they also address several of the more quantifiable regulating services, such as waste and nutrient flows, as discussed in Section 10.3.1.3. For example, the design of buildings can reduce construction waste by designing the building structure for disassembly, and incorporating materials with low lifecycle costs that are recycled, recyclable, and biodegradable.[309] Furthermore, the design of building spaces can promote occupants to take part in resource recycling and conservation behaviors, as discussed in Chapter 9.

The reduction of the ecosystem service footprints of urban core ecosystems, their inhabitants, and buildings has been found to improve the ecological functions of local ecosystems, by reducing the detrimental effects of urbanization on natural and constructed ecosystems.[183] For example, reductions in waste quantities alleviates the need for natural environments to be converted into landfills, as well as reduces potential water pollution from landfills, among other benefits.

§ 10.3.2.6 Assessing the effectiveness of existing general constructed environment design strategies to contribute to the functions of local + global ecosystems

However, as discussed in Section 10.3.1, these strategies do not comprehensively or effectively address the full range of supporting and regulating services of local urban core and natural ecosystems, thereby leading to environmental degradation.[71, 238] Indeed, directly addressing regulating and supporting services has been found to be more effective in this regard, compared to directly addressing provisioning and cultural services, within several contexts.[10, 33] Nevertheless, similar to the discussions in Sections 10.2.2 and 10.4, the relative impact of various design solutions depends on the context and goals of the project, as well as the quality and nature of the design solution. Moreover, the full value of individual services and functions have yet to be determined.[84]

Thus, more comprehensive design solutions than are currently in practice are necessary to effectively improve the functions of local and global ecosystems. For instance, design teams should look beyond material and system specifications in order to effectively address the regulating, supporting, and cultural services of local and global ecosystems.

For example, the negative effects of urban core ecosystems on the regulating and supporting ecosystem services of local ecosystems can be addressed directly by providing these services, as well as by reducing existing negative effects of urban core ecosystems on these services. However,

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as discussed in Section 10.4.9, due to the interrelated nature of individual ecosystem services, efforts to support one ecosystem service may directly and/or indirectly support and/or inhibit other ecosystem services.

A comprehensive overview of specific design strategies that improve the individual ecosystem functions of the local ecosystems is outside the scope of this chapter. Zari (2012) provides a review of several building scale design strategies that provide ecological functions and services. Nonetheless, a number of potentially effective design strategies, as well as relevant design issues, are discussed in Section 10.4.

§ 10.4 Identifying potential design issues + guidelines for developing constructed environments that effectively contribute to the functions of local + global ecosystems

Similar to the discussions in Chapter 8, and Sections 10.2.2 and 10.3.1, the potential contributions of constructed environments to the functions of local ecosystems are influenced by a number of factors, including contextual, temporal, scalar, and spatial issues. However, although urban areas are widely cited as prime contributors to the degradation of the functions of local and global ecosystems, there is scant existing research on how to evaluate the potential of a building to contribute to the functions of local ecosystems.[183, 341, 454] Furthermore, as discussed in Section 10.3.1, existing research suggests that the unique nature of urban core ecosystems requires different design solutions and strategies than those that are found to be effective in natural ecosystems. However, further research is needed to determine the effectiveness of existing and potential ecological design strategies and solutions to improve the ecosystem functions and services of local ecosystems, within the context of urban core ecosystems. The following subsections review a number of influential factors that should be accounted for when developing design strategies and solutions.

§ 10.4.1 Design for Context: Account for ecosystem functions of local + global ecosystems

Similar to the discussions in Section 10.2.2, 10.3.3, and Chapter 8, the influence of buildings on the ecosystem functions of the local constructed and natural ecosystems inherently depends on the dynamic state and functions of the local and global ecosystems. For instance, the quantification and valuation of ecosystem services are highly context dependent, because not all ecosystems provide the same services in the same quality and quantity over time, among other issues.[238] Therefore, it is important to evaluate the state of the functions of local constructed and natural ecosystems, in order to develop effective design solutions.

§ 10.4.1.1 Influence of context on the relative value of ecosystem functions

Furthermore, the relative importance of individual ecosystem functions, in terms of their effects on the state of the local constructed and natural ecosystems, is dependent on the context. For instance, the condition of the ecosystem functions within and adjacent to the building site, as well as the potential of the constructed environment to contribute to individual functions of the local ecosystems, is dependent on the location of the site within the urban core ecosystem.[35, 175] For example, the effects of urbanization on the functions of constructed ecosystems within urban areas are highly heterogeneous. For instance, different areas within urban core ecosystems function differently. This is partly due to the varying spatial characteristics of areas within individual ecosystems, such as their land use type and building density, as well as their dynamic processes and functions, such as shifting traffic rates and pollution sources.[183] For example, a building's district may provide district heating and cooling, thereby reducing the energy and resource demand of the district.

Thus, the relative importance of individual ecosystem functions is dependent on the context, which impacts which ecosystem functions are most important to address by design teams of individual building projects. Hence, in some contexts, it may be more important to improve the resilience of a specific ecosystem function, than to improve other relatively poor performing ecosystem functions. Design for resilience can be particularly important when a specific function is prone to malfunction or disturbance. Furthermore, due to the typically relatively low levels of ecosystem services, functions, and biodiversity within urban core ecosystems, addressing ecosystem functions effectively may be markedly different than within the context of natural ecosystems. These issues are discussed in more detail in Sections 10.4.8 and 10.4.9.

§ 10.4.1.2 Design for local versus global ecosystem functions

Nevertheless, it is important to note that as natural ecosystems continue to be degraded globally, and constructed ecosystems are further studied, there may be overriding ecosystem functions that become important to sustain globally. For example, there is evidence that carbon sequestration and emissions should be addressed globally.[71, 169] In other words, some ecosystem functions may be important to address within the context of any project, in order to sustain global and local ecosystems. However, further research is necessary to determine which functions need to be addressed globally. Furthermore, some ecosystem services may be highly valued by global human communities. These services may be at a higher risk of being degraded over time than other services and functions in some contexts, such as local fish and shellfish stocks, rainforest ecosystems adjacent to palm oil plantations and service roads, etc.

Moreover, it is important to consider that globally important ecosystem functions may not always be appropriate to address in individual building projects. For instance, in some cases, it may be more effective to address carbon emissions at the district, city, or national scale than at the building scale, and utilize the portion of the building project budget that would have been apportioned to carbon emissions reduction to water storage and filtration infrastructure. Thus, as part of the initial design process, design teams should compare the potential impact of addressing globally important ecosystem functions and other functions of the local ecosystems within the context of their individual building project. This design process will aid design teams in determining the most effective ways building projects can make positive contributions to the ecosystem functions of local and global ecosystems. However, it is important to note that further research is needed to effectively comparatively evaluate the effectiveness of addressing individual local and global ecosystem functions within the context of individual building projects. Nevertheless, it is evident that these global context issues should also be accounted for by ecological assessment methods.

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§ 10.4.1.3 Design for future context: Account for projected future functions of local + global ecosystems

As discussed in Section 10.2.2.4, contextual influences and interrelationships can be difficult to predict and fluctuate over time. For instance, the rapid growth and development within and around urban areas, as well as possible natural disturbances, can drastically alter the value of various ecosystem functions within relatively short time periods.[175] Thus, in order to develop effective design solutions, it is important to assess the future state of local and global ecosystems, as well as the projected future impacts of urbanization and natural processes, such as the effects of climate change, global and local population increases, and planned urbanization developments. These projections should be developed in order to ensure the evaluation of the species richness and performance of the ecosystem functions and services account for the ecosystem's future conditions, needs, and interrelationships.

However, it is important to note that there is considerable uncertainty about the effects of a number of factors, such as climate change, on the future state of local and global ecosystems.[467] Nevertheless, analytical projections of the future state of ecosystems can provide a general perspective of their possible future state, and can be used to develop guiding design principles.

§ 10.4.2 Design for connectivity: Account for inherent and potential interrelationships with local ecosystems + habitat patches

Design teams should evaluate the state of the ecosystem functions in adjacent areas and local ecosystems, in order to determine which can be connected to and/or addressed at the building site in a manner that increases the performance and distribution of local ecosystem functions, as well as to identify the ecosystem functions that are most important to address within the local context. For instance, the building site can support the distribution of functions throughout local ecosystems by supporting existing aerial corridors and habitat patch clusters, generating and distributing essential resources, as well as providing a diverse range of ecosystem functions. In addition, the development of ecological network connections have the potential to have a magnifying effect, as building sites may be able to repair key problems in the network. Potential habitat patch connection opportunities and issues are discussed in more detail in Chapter 11. Moreover, depending on the location of the building site, the design of the building can directly contribute to the resilience, functions, and integrity of local natural ecosystems. The benefits of design for resilience are discussed in more detail in Section 10.4.8.

§ 10.4.3 Account for scalar issues

The potential of individual constructed environments to contribute to the functions of the local ecosystems are limited by a number of scalar issues. For example, typical mid-size commercial office buildings in urban core ecosystems are spatially limited from providing large habitat patches and corridors. The inherent size and budget limitations of mid-size commercial office buildings also makes it considerably more challenging for these types of projects to significantly contribute to the functions of local ecosystems, compared to neighborhood and municipal scale design projects, as discussed in Chapter 8.

Moreover, the relatively small scale of constructed environments makes it particularly difficult to assess their effects on the functions of local and global ecosystems, within the context of current ecosystem function assessment methodologies, as discussed in Sections 10.2.2 and 10.3.2.

§ 10.4.4 Design for potential magnifier effects

Although the potential of individual constructed environments to positively promote the functions of local ecosystems is generally relatively low, as discussed in Section 10.4.3, building projects that develop effective design solutions can function as examples, and may even inspire future building developments to incorporate ecosystem functions into their projects. Furthermore, due to the inherent non-linearity of ecosystems, small modifications in the dynamics of an ecosystem can become magnified through interactions, and lead to large uncertainties in not only the rate, but the direction of change of system dynamics.[84] Therefore, seemingly small scale design strategies that address ecosystem functions at the building scale can potentially have a magnifying effect, resulting in an inordinately large effect on the ecosystem functions of local and global ecosystems.

§ 10.4.5 Design for economic costs

§ 10.4.5.1 Design for cost + value of ecosystem functions

The reduction of ecosystem services in urban areas generally results in some type of economic costs. However, the costs from the decline of ecosystem services are typically absorbed by the local municipality, making them less perceptible to the local community.[259] Thus, it is important to identify the beneficiaries of the provision of various ecosystem services within building projects, in order to identify potential funding streams, collaboration opportunities, and effective design solutions. For example, it is important to consider that the value of building scale solutions that improve the functions of local ecosystems to building developers and owners is typically different than the value of these solutions to municipalities and infrastructure providers.

This is partly because the latter typically finance the costs of ecosystem services, and haven't historically invested in building scale solutions. For instance, although green roofs function as storm water retention and filtration infrastructure, their construction and maintenance costs are typically allocated to the building owner. Some municipalities have recognized the benefits of building integrated infrastructure systems in reducing municipal infrastructure costs and vulnerability, and have developed methods to share the cost of these systems with building owners, such as through property and utility tax subsidies.[92, 303, 328]

§ 10.4.5.2 Design for budget constraints

The budgets of building projects influence the scope and effectiveness of ecological design solutions. Moreover, project budget constraints reinforce the necessity of identifying the ecosystem functions that are most important to address within the context of the project. These issues are discussed in more detail in Section 10.4.9.

§ 10.4.5.3 Design with technical + ecological resources

Furthermore, within urban core ecosystems, compact technological infrastructure solutions tend to be more cost effective than maintaining or restoring natural systems and processes within the urban core, due to the scarcity of available space, among other factors.[175] In addition, as discussed in Section 10.3.1.2, urban core ecosystems tend to have large quantities of imported resources, infrastructure, and technology. These parameters provide both unique opportunities and limitations, such as opportunities to develop technologies and infrastructure systems that generate ecosystem services and functions, as well as to effectively make use of imported and accumulated resources within urban areas.[9, 425]

For instance, there is evidence that the combination of technological and ecological systems and processes can be considerably effective, such as through the development of hybrid infrastructure.[292, 293, 296] Hybrid infrastructure are building scale design solutions that integrate municipal infrastructure systems into buildings and landscapes. The general performance goal of hybrid infrastructure is to improve the ecological, social, and economic performance of the building or landscape, as well as municipal infrastructure systems. Hybrid infrastructure systems often combine technological and ecological systems and processes. For instance, neighbourhood scale wastewater treatment plants can also provide high quality community social space and economic opportunities for the local community, as described in Chapter 9. Further discussions of the potential benefits of hybrid infrastructure, as well as example projects, are discussed in Chapters 9 and 12.

§ 10.4.5.4 Design for insurance value

The provision of redundant and supplementary ecosystem functions affords an inherent insurance value, by increasing the resilience and adaptive capacity of urban core ecosystems to disturbances. Potential disturbances can be both natural and socio-economic in nature, and can be irreversible or prohibitively costly to reverse. Moreover, the value of building scale ecosystem functions can increase exponentially as possible opportunities for substitution are lost, due to functional changes within the urban core ecosystem, such as from crises and development projects.[259] Design for resilience is discussed in more detail in Section 10.4.8.

§ 10.4.6 Design for new possibilities (functions + services)

As discussed in Section 10.2.1.1, new ecosystem services and functions are expected to be developed as technology evolves and researchers develop new ways to benefit from natural environments.[201]

Thus, design teams should consider the potential of their solutions to generate previously unconsidered benefits and services. For instance, the presence of vegetation can improve people's thermal comfort, thereby reducing the energy demand of the building, as described in Chapter 5. Furthermore, spatial infrastructure solutions, such as hybrid infrastructure, can be particularly effective means to incorporate and develop new functions, through the possible integration of building programs, occupants, infrastructure systems, and natural environments. For instance, the incorporation of natural environments into office building designs can improve worker performance, as described in Chapters 6 and 7, as well as reduce building energy demand, as described in Chapter 4.

§ 10.4.7 Design for project goals

By directly integrating ecological design solutions with overall building project goals, building owners and developers are provided greater economic and goal-oriented incentives to develop ecological design solutions, and the costs of ecological design solutions can be reduced by being integrated into the typical building costs. Moreover, a project goal oriented ecological design solution inherently encourages the design team to consider the potential benefits that the design solution can provide to the building owner and occupants, which can potentially lead to higher quality building solutions that provide a wider range of benefits.[292] Mangone (2011) discusses this topic in more detail.[296]

§ 10.4.8 Design for resilience

The resilience of ecosystem functions can be improved by addressing specific ecosystem functions in multiple locations and reducing local stressors, among other strategies.[105, 175] For instance, addressing already existing positive ecosystem functions of the urban core ecosystem at the building scale can increase the resilience of the urban core ecosystem.[259]

Furthermore, increasing the resilience of urban core ecosystems is particularly important in terms of reducing the impact of disturbances and crises, such as food shortages and natural disasters. For example, although the provision of ecosystem functions at the building scale, such as urban agriculture, may not be effective in a typical urban core ecosystem, they can become relatively valuable during a disturbance, as discussed in Section 10.4.5.[105, 464]

Moreover, it is important to note that design for resilience within urban core ecosystems is likely different than within natural ecosystems. For instance, resilience in natural ecosystems has been found to depend on the distribution, abundance, and dynamic interaction of species. To this end, ecosystems with high species function diversity have been found to have greater resiliency.[455] However, due to the typical low level of ecosystem services, functions, and biodiversity within urban core ecosystems, and since ecosystem functions within urban core ecosystems are typically provided by technical infrastructure systems, as discussed in Section 10.4.5, the resilience of urban core ecosystems are likely less dependent on biodiversity than natural ecosystems.[74, 175] This may be beneficial in some contexts. For instance, technical infrastructure, such as hybrid infrastructure, may be able to provide resilient ecosystem functions which are not reliant on biota. Nevertheless, improving the biodiversity of urban core ecosystems may improve their functions, as well as provide functions that would not otherwise be possible, as discussed in Section 10.2.5 and Chapter 11.

In addition, it is important to note that constructed environments can be designed to contribute to the resilience of local natural ecosystems, depending on a number of contextual factors, as discussed in Sections 10.4.1 and 10.4.2.

§ 10.4.9 Design for multivalence + trade-offs

The type, range, and relative abundance of functional traits present in a given community have been found to substantially contribute to the ecological integrity and services of natural ecosystems. Thus, the state and resilience of the functions of natural ecosystems, and the quantity of ecosystem functions present in these ecosystems, play key roles in the provision of ecosystem services.[20] Furthermore, in relation to the discussion in Section 10.2.1, due to the interrelated nature of ecosystem functions, the design of building scale design solutions for specific ecosystem functions has the potential to improve other negative and positive performing ecosystem functions. Therefore, building scale solutions may be able to effectively and efficiently address a diverse range of ecosystem functions and services, depending on the context of the project.

However, it is important to note that the improvement of a specific ecosystem function within natural ecosystems and regions typically negatively impacts other functions of the ecosystem or region.[74, 190, 397] Furthermore, some functions of natural ecosystems can negatively impact urban core ecosystems, defined as ecosystem disservices, such as microbial activity destroying wood structures.[175] Thus, design solutions that address ecosystem functions can involve trade-offs, providing both benefits and negative consequences simultaneously. Design teams should take into account performance trade-offs when developing and evaluating various potential design solutions.

Similar to the discussions in Sections 10.3.1 and 10.3.8, due to the typical low level of ecosystem services, functions, and biodiversity within urban core ecosystems, some trade-offs may be able to be avoided at the building scale within urban core ecosystems. However, existing examples demonstrate that trade-offs at the building scale may be inevitable. For instance, project constraints, such as relatively low budgets and site areas, may make trade-offs, in the form of which ecosystem functions can be addressed within a project, unavoidable.[74, 88]

Nevertheless, there is also evidence that some trade-offs are design issues, and therefore, can be avoided. For instance, although modern monoculture food production typically reduces biodiversity within regions, other agriculture methods can be beneficial to the biodiversity of local ecosystems, while also providing food services.[183, 223]

Due to these limitations, it is likely that building scale design solutions will address a limited range of ecosystem functions. Within this context, it becomes particularly important to identify the ecosystem functions that are most important to address within the local region, the effects of various design solutions on a range of ecosystem functions, as well as determining which functions can be most effectively addressed at the scale of individual buildings and building sites. Depending on the context, the relative value of addressing different ecosystem functions at the building scale will vary, as discussed in Sections 10.4.1 and 10.4.2. Furthermore, it is important to note that due to the difficulty in assessing the value of individual ecosystem services, as discussed in Section 10.2.2, it is difficult to assess the relative value of the trade-off functions. In other words, it is difficult to assess the impacts of addressing, or not addressing, a specific ecosystem function on other functions. Further research is necessary to identify and assess the inherent trade-offs of various design solutions, in order to determine the effects of building scale design solutions on the functions of constructed and natural ecosystems, and congruently, the potential of building scale design solutions to improve local and global ecosystems.

§ 10.4.10 Design spatially

The design of spatial infrastructure solutions, such as hybrid infrastructure, can be particularly effective at addressing multiple functions simultaneously, effectively, and economically.[245, 292, 296] For instance, the development of spaces that incorporate vegetation and natural habitats can address numerous ecosystem functions simultaneously. For example, bioswales can reduce stormwater overflows, filter air and water pollutants, increase stormwater retention and site water infiltration rates, increase biodiversity, and if designed to effectively interact with building occupants, promote ecological behavior, productivity, and well-being, among other benefits.[47, 245, 300] Furthermore, spatial infrastructure solutions can be more cost effective than standalone solutions by being incorporated into building designs and typical building systems in effective ways, as well as by providing more psychological and social benefits. For instance, spatial infrastructure solutions can be designed to be more engaging, multifunctional, and interactive than standalone solutions, as discussed in Section 10.4.9, and Chapters 6, 7, and 9.

§ 10.4.11 Design for ecological behavior

Urban core ecosystems provide opportunities to influence the behavior of relatively large human populations. The design of constructed environments allows design teams to develop opportunities for occupants to have positive experiences that promote a diverse array of ecological behaviors, and provide a myriad of benefits to occupants. Potential effective strategies and benefits of the design of building spaces on people's ecological behavior are discussed in more detail in Chapter 9, as well as the difficulty of quantifying the benefits of design for ecological behavior.

§ 10.4.12 Design for biodiversity

The design of constructed environments can also contribute to the biodiversity of local constructed and natural ecosystems, and in doing so, can potentially provide and improve various ecosystem functions.[257, 281] However, it is important to note that the value of addressing biodiversity within a specific building project is contextual, and may not be effective in some cases. Furthermore, design for biodiversity strategies must take into account the unique opportunities and limitations of typical urban core ecosystems. These issues are discussed in more detail in Section 10.2.5 and Chapter 11.

§ 10.4.13 Collaborate with local ecologists

The inherently contextual nature of ecosystems and constructed environments, as discussed in Sections 10.2.2 and 10.4.1, necessitates the development of ecosystem specific function analysis, in order to assess the state of local constructed and natural ecosystems, as well as the impact of various design solutions. Although there are currently limitations to the depth and accuracy of existing ecosystem function assessment methods, as discussed in Sections 10.2.2, 10.2.4, 10.3.1, and 10.3.2, local ecologists can aid in the development of more specific assessments of local ecosystems than currently available general ecosystem assessment tools. For instance, ecologists can analyze the performance of the various ecosystem functions of an ecosystem through both bottom up and top down approaches, in order to identify poor performing and high performing ecosystem functions, identify opportunities to improve poor performing ecosystem functions, identify potential threats and disturbances to ecosystem functions, and help prioritize the need to address the various poor performing ecosystem functions.[88, 325] Ecologists can also help determine how urbanization is affecting local natural and constructed ecosystems, as well as help identify effective methods to improve the functions of the local ecosystems.

§ 10.5 Chapter Conclusion

Thus, it is apparent that constructed environments and ecosystems substantially influence the functions of local and global ecosystems in a myriad of ways. However, the potential influence of constructed environments on the functions of local ecosystems is dependent on a number of dynamic spatial, contextual, and temporal issues. Moreover, effective, comprehensive methods to assess the state of the functions of individual ecosystems, as well as methods to assess the influence of individual constructed environments on the functions of local ecosystems, have not yet been developed. Therefore, future research should investigate more effective assessment methods, in order to promote the generation of design solutions and constructed ecosystems that improve the functions of local and global ecosystems.

Nevertheless, several promising methods to assess the effects of constructed ecosystems and environments on the functions of local ecosystems have been identified and discussed in this chapter, including potentially effective combinations of existing assessment tools, as well as innovative assessment methods that were identified based on the results of existing literature. These assessment methods can aid future design and research projects. Moreover, a number of influential design guidelines and issues were identified from the results of existing literature, which can aid design teams and future research projects in developing constructed environments that promote the functions of local ecosystems. For instance, existing research demonstrates that the design of constructed environments to promote ecological behavior, as discussed in Chapter 9, as well as design to improve the biodiversity of local ecosystems, as discussed in detail in the following chapter, can also positively affect the functions of local and global ecosystems, depending on the design solution. Taken together, the findings discussed in this chapter demonstrate that there are diverse opportunities for constructed environments and ecosystems to improve the functions of local ecosystems. Moreover, the design of constructed environments and ecosystems to improve the functions of local ecosystems can provide diverse benefits to human communities and natural ecosystems.

11 Constructing Biodiversity

Exploring the potential of the design of constructed environments to improve the biodiversity of local and global ecosystems

§ 11.1 Introduction

Although the relative scale of influence of biodiversity on the integrity of ecosystems is currently under considerable debate, as discussed in Chapter 10, it is important to consider that existing literature indicates that the ecological integrity of ecosystems are partially dependent on their biodiversity. For instance, species loss has been found to be an indicator of ecological integrity, and typically precedes changes in an ecosystem's functions and health.[374] To this end, this chapter explores the potential of the design of constructed environments to improve the biodiversity of local ecosystems.

§ 11.1.1 Defining the current effects of human communities on the biodiversity of natural ecosystems

§ 11.1.1.1 Global quantity of species + natural ecosystems declining

Although it's difficult to effectively quantify global species richness and individual species quantities, partly since a myriad of species are yet to be discovered and quantified, extant research indicates that global and local biodiversity rates have decreased significantly in the last 50 years. For instance, the World Wildlife Fund's 2014 Living Planet Report found that the populations of wild vertebrate species declined by 52% between 1970 and 2014. During the same 44 year period, terrestrial and marine species declined by 39%, while freshwater species declined by 76%.[482] Similarly, the Millenium Ecosystem Assessment (MA) by the UN in 2005 found that in the last forty years, approximately 20% of measured coral reefs were destroyed, and another 20% were degraded. Around 35% of measured wetlands, which was estimated to encompass approximately half of the world's mangrove area, was also destroyed. In addition, approximately 50% of the world's commercial marine fisheries were found to be fully exploited, while an additional 25% were found to be overexploited.[130]

§ 11.1.1.2 Preservation + restoration of additional natural ecosystems necessary to sustain biodiversity of local and global ecosystems

Existing research indicates that only 10-15% of the global terrestrial area, and 2.8% of the global marine area, is currently designated as protected area. It is important to note that these calculations did not account for several confounding factors that could lead to overestimation, including overlaps of protected areas. Furthermore, this proportion varies substantially by ecosystem type, with ecosystem types that are difficult to develop, in terms of cost, etc., such as mountainous terrain, receiving considerably more protection. Indeed, a number of historically commonplace ecosystem types receive little to no protection.[221, 299, 326, 414] In addition, the quality of existing and proposed protected areas have been found to be problematic in many cases, such as the presence of substantial gaps in protected areas that both inhibit the ability of the area to sustain critical ecological processes and species habitat requirements, as well as maintain resilience in regards to a diverse range of disturbances. The allowance of industrial and recreational disturbances within a number of protected areas, such as mining and logging, also substantially reduces the quality of these areas, in terms of their ability to conserve biodiversity.[299, 326]

Indeed, a number of research findings suggest that nature reserves are insufficient as a sole strategy to sustain adequate levels of biodiversity within local and global ecosystems.[174, 281, 314, 321, 384] To this end, a review of existing literature by Noss (2012) indicated that a 50% regional natural ecosystem preservation goal is an appropriate general guideline, although it is important to note that the precise quantity of area of a region that is necessary to preserve its biodiversity inevitably varies on an individual basis due to numerous contextual factors.[342] Thus, the results of existing literature clearly indicate that it is necessary to preserve a substantially greater proportion of local and global regions than is currently common practice, if biodiversity within local and global ecosystems is to be sustained.

§ 11.1.1.3 Identifying key contributing factors to the loss of biodiversity within local + global ecosystems

In order to promote biodiversity in local and global ecosystems, it is important to identify the current drivers of biodiversity loss. As discussed in Chapter 8, direct habitat alteration is the primary cause of biodiversity loss in local, regional, and global ecosystems. Moreover, the establishment and expansion of urban areas is one of the primary drivers of natural habitat alteration, and typically disrupts the ecological integrity and biodiversity of pre-existing and adjacent natural ecosystems.[130, 257, 341] For instance, cities alter the landscapes and related biodiversity patterns at the city scale, as well as at the regional and global scales, through their individual and collective impacts on local and global ecosystems.[17, 195] In addition, urban development produces some of the greatest local extinction rates, endangers more species than any other human activity in the US, frequently eliminates a large majority of native species in local ecosystems, and is one of the leading causes of species extinction in the world.[313, 320, 321] Furthermore, urbanization has been identified as a primary cause, by itself or in association with other factors, for declines in more than half of the species listed as threatened or endangered under the U.S. Endangered Species Act. Hence, the number of threatened species in local natural ecosystems typically increases as urban areas expand.[455] This is partially because cities tend to be established in biodiversity 'hotspots', disrupting key ecological interrelationships and species. Cities commonly develop in biodiversity 'hotspots' because these areas contain diverse resources that are valuable for human communities.[91, 280] Thus, in order to preserve and restore the biodiversity of local and global ecosystems, it is important to determine how to reduce the negative impacts of cities on the biodiversity of local and global ecosystems, as well as how cities can promote biodiversity.

§ 11.1.2 Defining the scope of the research

§ 11.1.2.1 Primary research objective

The primary objective of this chapter is to explore the potential of constructed environments to improve the biodiversity of local constructed and natural ecosystems.

§ 11.1.2.2 Research boundary limits

It is important to note that suburban and urban core ecosystems tend to be categorized together as urban ecosystems in existing literature.[257] For instance, existing studies that were conducted within cities, and references to existing studies within existing literature, commonly either do not distinguish the specific type of constructed ecosystem that was evaluated in the discussed studies, or evaluate overall urban areas, rather than individual constructed ecosystems within urban areas. Moreover, urban core ecosystems have received relatively less attention in existing literature than urban areas.[281] However, urban core ecosystems have distinct characteristics, functions, and biodiversity, as discussed in Section 11.2.6, as well as Chapters 8 and 10. Therefore, the physical context of studies from existing literature, and their applicability to urban core ecosystems, are included in the discussions in this chapter when possible. Further research is needed to identify and evaluate the relative effectiveness of biodiversity design solutions and strategies for different types of constructed ecosystems, as discussed in more detail in Section 11.8. Nevertheless, the various types of ecosystems that comprise urban areas, such as suburban, industrial, horticultural, and urban core ecosystems, should be addressed by design teams and ecological performance assessments, in order to effectively determine the potential of cities to improve the biodiversity of local and global ecosystems. Moreover, it is important to consider that solutions that are applicable to urban core ecosystems can sometimes be applicable to other constructed ecosystems as well.[257, 281] Thus, studies focused on overall urban areas are also included in the discussions in this chapter.

It is important to note that the dynamic processes and interrelationships of complex systems, such as ecosystems, are difficult to evaluate, as discussed in Chapters 8-11. For instance, human activities typically generate unintended and unforeseen consequences, with variable levels of severity of resultant effects. For example, constructed environments within urban areas have been found to radically alter the trophic structures and functions of ecosystems, thereby altering the interrelationships and resource needs of the local species.[139] Similarly, it is challenging to assess the effects of making changes to constructed and natural ecosystems through human development and disturbances, including ecologically minded building construction. Thus, effectively evaluating the effects of various design solutions, in terms of their effects on the biodiversity of local ecosystems, is difficult. For instance, most changes to ecosystems result in unintended consequences that affect the inherent dynamic, complex, and interrelated nature of constructed and natural ecosystems.

Nevertheless, given the current and projected future dire state of natural and constructed ecosystems, it is imperative that effective design solutions for improving the biodiversity of constructed and natural ecosystems be explored and developed. Just as human development has severely negatively affected most local and global ecosystems, humanity can develop methods to positively affect ecosystems, sometimes in ways that benefit both human and natural communities.[296, 299, 384] Thus, despite these limitations, this chapter explores a number of potentially effective ways constructed environments can positively contribute to the biodiversity of local ecosystems.

§ 11.1.2.3 Sub-research objectives

The potential of a number of design strategies and solutions to improve the biodiversity of local ecosystems through the design and operation of building projects are explored in this chapter, in order to effectively address the primary research objective of this chapter. These diverse explorations and discussions can be organized into sub-research objectives, as outlined below:

- Identify the influence of the context of building projects on the potential of constructed environments to promote biodiversity
- Identify contextual design issues that design teams should address
- Explore the qualities of habitat patches that influence the potential of constructed environments to promote biodiversity
- Explore the relative value of incorporating various types of habitats into constructed environments that are situated within urban core ecosystems, in terms of improving the biodiversity of local ecosystems
- Explore the potential value of supporting and sustaining various species within constructed environments, in terms of improving the biodiversity of local ecosystems

These sub-research objectives are addressed in individual sections within this chapter, as outlined in Section 11.1.2.4.

§ 11.1.2.4 Chapter Outline

The influence of constructed environments on the biodiversity of local ecosystems is dependent on a number of contextual issues, as discussed in Sections 11.2 and 11.4. Thus, in order to address the sub-research objectives of this chapter, it is important to understand effective ways that urban core ecosystems and urban areas can improve the biodiversity of local ecosystems. To this end, Section 11.2 identifies existing biodiversity goals that have been developed for urban areas, as well as reviews a number of issues that should be taken into account when developing biodiversity goals and assessing the effectiveness of various design solutions. Section 11.3 identifies the general potential of urban areas and constructed environments to improve the biodiversity of local ecosystems, while Sections 11.4-11.7 discuss more specific design strategies and solutions for constructed environments to improve the biodiversity of local ecosystems.

Specifically, the effects of the context of building projects on the potential of constructed environments to promote biodiversity are explored in Section 11.4. This exploration includes the identification of contextual design issues that design teams should address. Habitat quality issues that can influence the ecological performance of constructed environments are reviewed in Section 11.5, while the types of habitats that existing literature indicates can be beneficial to integrate into building environments that are situated within urban areas are discussed in Section 11.6. The potential value of designing constructed environments to support and sustain different types of species are explored in Section 11.7. A general overview of the structure of this chapter is illustrated in Figure 11.1.

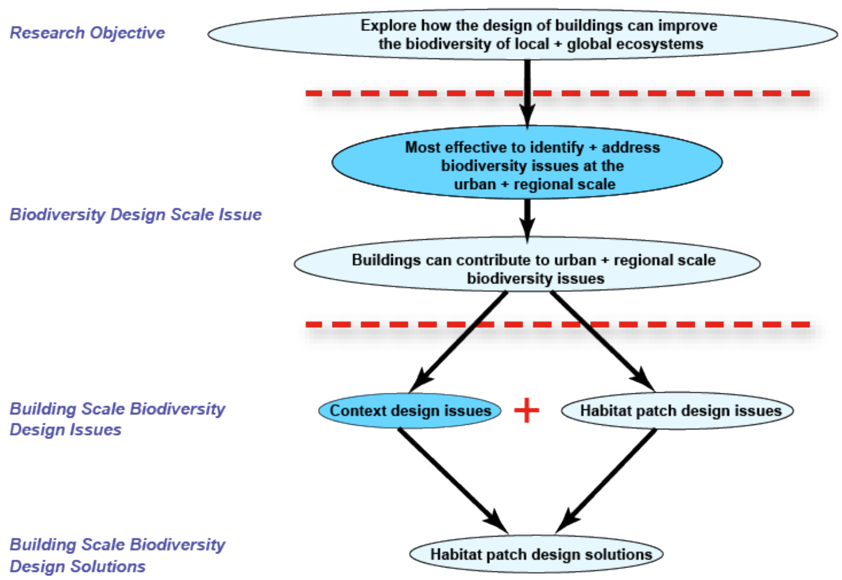

FIGURE 11.1 Constructing biodiversity chapter overview

§ 11.2 Identifying general biodiversity goals for the design of urban areas

§ 11.2.1 Identifying existing biodiversity goals for urban areas

There is substantial evidence that urban areas can promote biodiversity, as discussed in Section 11.2.6, Section 11.3.1, and Chapter 8. Moreover, existing literature indicates that addressing biodiversity in cities is vital to maintaining biodiversity within local and global ecosystems, due to the inadequacy of nature reserves to sustain the biodiversity of local and global ecosystems.[174, 281, 314, 321, 384]

To this end, a number of biodiversity goals for urban areas, which can be referred to as urban biodiversity goals, have been developed. However, the relative value of various biodiversity goals for urban areas is still unclear. For example, there is evidence that urban areas can provide and maintain self-sustaining populations of species, including rare and endangered native species and habitats.[257, 281] However, due to a number of contextual and spatial factors discussed in Sections 11.4 and 11.5, spaces within urban core ecosystems aren't always able to generate self-sustaining species populations. Yet these spaces can provide temporary habitat patches that provide essential resources and interconnections between higher quality habitat patches and natural areas.[174] There is also evidence that providing resources and habitat for priority species that are present within urban reserves and adjacent natural ecosystems can be an effective biodiversity goal for urban areas.[231] In addition, sustaining functionally diverse species richness in urban areas can also be beneficial, because it can result in an increase in the quantity and resilience of ecosystem functions and services in some cases.[174, 314] Moreover, an overview of a diverse range of existing and proposed biodiversity design solutions for constructed environments within urban areas, such as captive breeding programs, gene banks, and the provision of actively maintained habitats, are discussed in Section 11.5.

§ 11.2.2 Identifying current limitations of identifying effective biodiversity goals for urban areas

It is currently difficult to identify the most effective ways that urban areas can improve the biodiversity of local and global ecosystems. This is partly because the value and quality of biodiversity within urban areas is under debate. In addition, the relative value of different biodiversity strategies is inherently contextual, as discussed in Section 11.4. Furthermore, the current ambiguity of the effectiveness of various urban biodiversity goals and strategies may be partly due to the fact that comparatively little research has been conducted on urban areas.[139, 183, 313] Moreover, even less research has investigated how constructed environments can positively impact the biodiversity and ecological integrity of local and global ecosystems.[257, 281]

§ 11.2.2.1 Current limitations in identifying effective biodiversity design strategies for urban areas

It is important to note that existing research on the biodiversity of urban areas has been focused on evaluating typical conditions of urban areas.[21, 174, 257] Relatively little research has been conducted on identifying and evaluating important physical characteristics of constructed environments, in terms of promoting biodiversity, such as minimum habitat patch sizes, shapes, and connectivity needs for various species within the context of urban core ecosystems. Moreover, existing studies tend to evaluate the potential of typical constructed environments and ecosystems to promote various biodiversity goals, rather than evaluating the potential of constructed environments that are designed to promote biodiversity. For instance, there are not many existing studies that explore the potential of innovative constructed environment and ecosystem design strategies and solutions to promote biodiversity. Despite this lack of existing research, the results of extant literature indicate that further research into identifying and evaluating the potential of constructed ecosystems and environments to promote biodiversity within local ecosystems will lead to effective, multi-scalar solutions and strategies.[174, 281] In order to improve the validity of future research, researchers should ensure that the performance of constructed ecosystems and habitats within urban areas are evaluated at the appropriate scale, in relation to their research questions and context.

§ 11.2.2.2 Current limitations in identifying effective general habitat patch design strategies

Moreover, it is important to consider that a number of urban biodiversity design strategies require the provision of habitats within urban areas. However, the types, characteristics, quality, and effectiveness of habitats that are possible within urban areas are currently being identified and evaluated. For instance, there is currently a debate about whether the typical design of constructed environments inherently generates novel habitat patches and environments, or if constructed environments are not necessarily novel, but rather tend to be constructed analogues of regional habitats. Both of these perspectives provide site scale design guidelines. For instance, a novel ecosystem perspective promotes determining the biodiversity potential of the site from its current state, including its biotic and abiotic properties (site based design approach).[257] On the other hand, rather than considering project sites within urban areas as novel ecosystems, a reconciliation ecology perspective promotes considering existing and future constructed environments as constructed analogues of regional habitats, whose species are currently prohibited from colonizing the site due to dispersal barriers (regional based design approach).[281] This regional reconciliation perspective thus contends that constructed environments within urban areas can facilitate habitat for a more diverse range of species than the novel ecosystems approach, because a reconciliation ecology perspective does not assume that species that aren't present on a particular site are inherently incompatible with the conditions of the site. Furthermore, a reconciliation ecology perspective promotes identifying regional habitats that constructed environments can be designed to be structurally or functionally similar to, in a manner that supports indigenous biodiversity. Section 11.6 discusses reconciliation design strategies in more detail. Finally, it is important to note that both of these strategies can support a range of urban biodiversity goals.

§ 11.2.2.3 Current limitations in identifying effective biodiversity performance indicators

The effectiveness of existing biodiversity performance indicators are currently under debate, similar to the debate about effective design for biodiversity goals. For instance, indicator species richness and related diversity indices have been used as biodiversity performance indicators of natural and constructed ecosystems in existing literature.[257, 455] However, there is substantial evidence that these indicators are not effective biodiversity performance indicators.[206, 257, 365] To this end, Kowarik (2011) suggests that the ability of an ecosystem to support self-sustaining species populations is a more valid biodiversity performance indicator for ecosystems.[257] However, as discussed throughout Section 11.2.2, the value of various proposed biodiversity goals, and thereby biodiversity performance indicators, is currently being debated, and is context dependent. Thus, it is important to note that effective performance metrics for evaluating the biodiversity of local ecosystems is context dependent, and particularly within urban areas, depends on the goals and potential of constructed ecosystems to contribute to the biodiversity of the region.

Moreover, the inherent complexity of urban areas, including the influences of human communities on local ecosystems, make it more difficult to evaluate the effects of urban areas on the biodiversity of local ecosystems, than to evaluate the effects of natural ecosystems on the biodiversity of the region. In addition, the complexity of urban areas makes the evaluation of the effects of changes to urban areas on the biodiversity of the local ecosystems considerably more complicated, as discussed in Section 11.2.6.2.[139] In turn, this makes the identification of effective biodiversity performance indicators for urban areas and constructed environments difficult.

§ 11.2.3 Considering the relative value of addressing ecosystem functions and ecological behavior, in terms of effectively improving the biodiversity of local ecosystems, from the context of urban core ecosystems

In contrast, there is also evidence that indigenous species richness and ecosystem services are typically low within urban core ecosystems.[21, 313, 455] Some researchers have interpreted this evidence as implying the *potential* of urban core ecosystems to provide ecosystem services, as well as to foster indigenous species richness, is low. From this perspective, strategies that limit the expansion and impacts of urbanization on surrounding natural ecosystems are the primary design for local biodiversity goals, such as reducing urban sprawl, promoting ecological behavior, and reducing the ecological footprint of urban areas, as discussed in Chapters 8-10. However, as discussed in Section 11.2.2, the potential of urban areas to promote biodiversity is not yet well understood, and is inherently context dependent. Further research is necessary to determine effective urban biodiversity design strategies, as discussed in Section 11.3.

§ 11.2.4 Importance of accounting for the interrelationships between design for an ecosystem's functions, biodiversity, and ecological behavior

Design for the biodiversity and ecosystem functions of local ecosystems is inherently interrelated, as discussed in Chapter 10. For instance, there is evidence that improving the biodiversity of ecosystems typically results in the provision of additional ecosystem services.[455] Furthermore, the provision of habitats in urban core ecosystems can also contribute to promoting ecological behavior, by providing urban dwellers with opportunities to have positive experiences with natural environments and stimuli. However, the effectiveness of these spaces to promote ecological behavior depends on their design, as discussed in Chapter 9. In addition, as discussed in Chapter 9, the provision of habitats within urban core ecosystems may promote people to move to cities, as part of a recursive nature-experience feedback. Therefore, the provision of biodiversity in urban core ecosystems may have a magnifier effect, by potentially reducing rural and suburban developments, as well as suburban sprawl, as discussed in Chapter 9. Additionally, in some contexts, addressing specific ecosystem functions can sometimes be the most effective method to support local biodiversity, such as when an urban area pollutes a river, to the point which the adjacent riparian corridor is substantially damaged. Thus, in order to determine the most effective biodiversity goals for a given project, the negative effects of the functions of urban core ecosystems on the biodiversity of local constructed and natural ecosystems need to be evaluated.

Furthermore, it is important to note that limiting the expansion and impacts of urbanization are important for conserving the biodiversity and ecosystem functions of local and global ecosystems, regardless of these conflicting design perspectives. Indeed, the elimination of suburban and rural developments would allow for substantially greater areas for nature reserves, and in many cases, achieve the 50% regional natural ecosystem preservation goal proposed by Noss (2012).[342] For instance, the elimination of rural developments in the US would allow for more than 25% of the country's terrestrial land area to be converted to nature reserves, as well as restore and strengthen ecological interconnections between existing natural ecosystems.[65]

§ 11.2.5 Identifying the influence of context on the effectiveness of various biodiversity goals for urban core ecosystems

In terms of identifying the most important biodiversity goals for a given urban core ecosystem, it is important to note that the relative value of various biodiversity goals for urban areas are inherently contextual, similar to the discussion of the contextual issues that affect an urban core ecosystems' influence on the integrity and functions of local ecosystems that are discussed in Chapters 8 and 9. For example, Kowarik (2011) suggests that urban areas that are adjacent to biodiverse, stable natural ecosystems typically are not be able to contribute to the biodiversity of adjacent natural ecosystems as much as urban areas that are adjacent to less stable natural ecosystems that have low species richness.[257] Furthermore, the potential of urban core ecosystems and urban areas to contribute to the biodiversity of local and global ecosystems depends on a number of dynamic spatial and temporal contextual issues, at the scale of the local constructed and natural ecosystems, the region, and the world. However, a comprehensive review of the myriad of factors that influence the potential of urban areas to promote biodiversity in local constructed and natural ecosystems is outside the scope of this chapter. Nevertheless, this chapter provides a review of specific building scale issues that existing literature indicates should be considered when developing urban areas to improve the biodiversity of local ecosystems. Furthermore, it is important to consider that a number of the discussed building design issues, particularly those discussed in Section 11.4, are directly relevant to urban scale design issues as well.

§ 11.2.6 Identifying the current state of biodiversity within typical urban areas

Several researchers have found evidence that cities are structurally, functionally, and biologically homogenous. According to this perspective, cities are more likely to have species, structures, and functions that are more in common with other cities around the world than adjacent natural ecosystems.[183, 313]

§ 11.2.6.1 Urban areas not effectively promoting biodiversity

However, the evidence that is cited for these generalizations on the homogenization effects of urbanization on biodiversity are largely based on studies focused on individual cities, rather than global scale analyses.[21] Furthermore, there is substantial evidence that the biodiversity potential of constructed environments is a design issue, and that urban areas can effectively promote local and global biodiversity goals. For instance, Aronson(2014) compiled the 'largest global dataset to date' of birds and plants in cities throughout the world.[21] The results of this study indicated that the majority of the species in urban areas were native to the individual cities, and that very few species were common among cities throughout the world. These results suggest that cities have the potential to foster habitat for indigenous species, and are not more biologically similar to each other than local natural ecosystems. However, the results also indicated that on average, cities are currently ineffective at promoting biodiversity, with only 8% of native bird species and 25% of native plant species present, in comparison to the estimated density of these species in local non-urban areas. In addition, the density of plant and bird species was positively associated with the quantity of vegetated land cover.[21] Thus, although cities are capable of supporting the biodiversity of local ecosystems, the current design of constructed environments and ecosystems are typically not effective at promoting biodiversity, and should be improved.

§ 11.2.6.2 Urban areas have markedly different trophic dynamics than natural ecosystems

Species within urban areas are interconnected via their complex interactions that encompass food webs. For instance, every species within urban areas interacts with at least one other local species. Moreover, a number of direct and indirect ecosystem functions within urban areas are dependent on the state of the local food webs.[10] Therefore, it is important to understand the state of local food webs, and the ways the processes and behaviors of human communities alter food webs, in order to determine how to effectively improve the biodiversity and ecosystem functions of local ecosystems.[139]

It is important to consider that the trophic dynamics developed within urban areas are markedly different than those of local natural ecosystems, and are difficult to evaluate. For instance, top predators are commonly excluded from urban areas, nonnatives are introduced, and native species are sometimes eliminated, which results in dynamic, complex shifts in the trophic dynamics of urban areas that are difficult to predict, compared to local natural ecosystems.[109, 379] For example, a literature review by Faeth (2005) found that the development of the Phoenix urban area drastically altered the composition of species, increased plant productivity, and increased the abundance of resources within the urban area, compared to local natural ecosystems. These changes, among others, reduced the seasonal and annual variations in several common urban species. Specifically, the reduced risk of predation for birds within this urban area increased their abundance, causing substantial changes to the abundance and composition of other species.[139] Thus, in order to effectively assess the biodiversity of local ecosystems, it is important to evaluate the state of the trophic dynamics of urban areas.

Moreover, it is important to note that the trophic dynamics of urban areas are dependent on a number of contextual factors, are strongly influenced by the dynamic processes and behavior of human communities, and will vary between different urban areas, as discussed in Section 11.4. In addition, the trophic dynamics of urban areas tend to be considerably more complex than local natural ecosystems. This increased complexity makes it more difficult to effectively evaluate the current state of biodiversity of urban areas and local natural ecosystems, as well as more difficult to effectively evaluate the potential effects of design solutions on the biodiversity of local ecosystems, as discussed in Section 11.2.2.3.[73, 139] Therefore, it is important to develop further research into methods to effectively understand and evaluate the trophic dynamics of urban areas. Nevertheless, existing findings, such as those presented in this subsection, can help design teams take into account the trophic dynamics of urban areas during the design process.

§ 11.3 Exploring the potential of constructed environments + urban areas to improve the biodiversity of local ecosystems

§ 11.3.1 Exploring the potential of urban areas to contribute to the biodiversity of local and global ecosystems

There are successful examples of how each of the urban biodiversity goals discussed in Section 11.2 can be accomplished within typical urban areas.[174, 180, 257, 281] For instance, although a number of city scale biodiversity studies have found a decrease in rare and endangered species in urban areas,[18, 39] there is evidence that this issue is a design problem, and that urban areas can effectively promote native species richness. For example, Celesti-Grapow & Blasi (1998) found that a number of Italian cities had substantially diverse vegetation species, and that these species were more similar to local natural ecosystems than other regional cities. Furthermore, there are a number of studies at the habitat scale that indicate the design of constructed environments and ecosystems can successfully promote local biodiversity. Several of these studies are discussed in Section 11.3.2. In terms of human behavior impacts, McKinney (2006) found the types of vegetation and pets people purchase in cities throughout the world were similar, which indicates that vegetation diversity can be improved by addressing the ecological behavior of local communities, such as providing access to local species.[313] In addition, Section 11.5 provides a more detailed review of the potential of different types and qualities of habitat patches within urban core ecosystems to promote biodiversity.

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The design and performance evaluation issues discussed in this subsection and Section 11.2 can support future research that is focused on the identification and development of effective ecosystem scale biodiversity design and evaluation goals. Moreover, these discussions can aid design teams in developing ecosystem scale design strategies and solutions that effectively improve the biodiversity of local ecosystems.

Exploring the potential of constructed environments to improve the biodiversity of local ecosystems

There is relatively scant existing literature on the positive potential of buildings to promote biodiversity, in comparison to research that has been conducted on habitat scale solutions that promote biodiversity in natural ecosystems.[257, 281] Nevertheless, existing research on the potential of roofs, gardens, walls, and fragmented habitat patches demonstrate that individual buildings can have a positive impact on the biodiversity of local ecosystems.

§ 11.3.1.1 Identifying the potential of spatial building scale biodiversity design strategies

It is important to note that the majority of existing research that has evaluated the potential of buildings to promote biodiversity, besides existing literature on the potential of surrounding landscapes, has been focused on the potential of the exterior skin of the building to function as a habitat patch, primarily through green roofs and walls, as well as gardens. [174, 257, 263, 281, 411, 412, 437] Nevertheless, extant literature indicates that the integration of spatial environments, such as landscapes, into buildings can be effective, in terms of promoting biodiversity, as well as in terms of providing benefits to building owners and occupants.[98, 138, 244, 292] For instance, diverse natural habitat types have been incorporated into buildings for centuries. Zoos, wildlife rehabilitation centers, Victorian greenhouses, and botanical gardens provide examples of how buildings can support local habitat preservation, restoration, and maintenance, support and maintain local species' subpopulations, particularly rare and endangered species, provide temporary habitat patches, contribute to ecological corridors, provide opportunities to overcome dispersal barriers for indigenous species, function as gene banks for indigenous flora and fauna, and promote ecological behavior, among other benefits.[98, 124, 281, 366, 411] Moreover, existing literature indicates that habitat patches which are too small to adequately function as habitats individually, such as residential gardens, are able to function as habitats if they are relatively closely adjacent to other small habitat patches. This is because the individual gardens function as a habitat patch as a group.[125, 174] In terms of habitat structure, plants that are indigenous to regional rock outcrop ecosystems have been found in some cases to be abundant in constructed hardscape areas.[180, 281]

Thus, buildings can potentially promote the biodiversity of local ecosystems in diverse ways. Furthermore, the design of spatial environments to address regional biodiversity goals can provide effective opportunities to address biodiversity goals at the building scale. Moreover, spatial environments provide opportunities to promote biodiversity in ways that are not possible through addressing biodiversity through the design of exterior surfaces. To this end, the potential psychological and ecological behavior benefits that can be generated when people interact with spatial natural environments are discussed in Chapters 6,7, and 9.

§ 11.3.1.2 Identifying building scale biodiversity performance indicators

In order to evaluate a building's potential contribution to the biodiversity of local ecosystems, both potential and existing positive and negative regional biodiversity performance parameters should be identified and evaluated. The importance of addressing regional scale biodiversity issues is discussed in greater detail in Section 11.4. However, a comprehensive design support system, including design guidelines and a metric system for evaluating the potential of buildings to contribute to the biodiversity of local constructed and natural ecosystems, has not yet been developed. Similarly, at the ecosystem scale, effective biodiversity performance indicators, as well as the relative value of various biodiversity goals for constructed ecosystems, are context dependent, and are currently under debate, as discussed in Sections 11.2 and 11.4. Since this chapter is focused on the scale of individual buildings, a comprehensive review of ecosystem scale factors is outside the scope of this chapter.

Nevertheless, metrics and solutions that have been developed for evaluating the quality of constructed and natural habitat patches, are in some cases applicable to buildings and building sites. However, it is important to note that the application potential of these evaluation metrics and design strategies to buildings and constructed ecosystems is inherently contextual, and in a number of cases, require further validation. Furthermore, potential building specific biodiversity performance indicators and solutions have also been identified, and in some cases, evaluated.[174, 437, 486] Existing and potential building scale biodiversity performance indicators are discussed throughout Sections 11.4, 11.5, 11.6, and 11.7.

§ 11.3.2 Exploring effective building scale biodiversity design solutions

The following sections review a number of design issues, strategies, and solutions that should be considered when designing buildings to promote the biodiversity of local ecosystems. These discussions provide opportunities to identify, and in some cases comparatively evaluate, potentially effective design guidelines, solutions, and biodiversity performance metrics and indicators. Moreover, this discussion is intended to be an initial step towards the development of an effective building scale design for biodiversity support system.

Specifically, Section 11.4 discusses contextual design issues that should be taken into account when developing constructed environments to promote biodiversity. Section 11.5 reviews a number of important habitat quality issues, while Section 11.6 explores the types of habitats that are important to foster within urban core ecosystems. Moreover, Section 11.7 explores the value of sustaining and support different types of species through the design and operation of constructed environments within urban core ecosystems.

§ 11.4 Identifying influential building context biodiversity design issues

The potential of buildings to contribute to the biodiversity of local ecosystems inherently depends on a myriad of dynamic spatial and temporal contextual issues, at the scale of the site, neighborhood, local constructed and natural ecosystems, region, and the world, similar to the contextual issues that affect a building's influence on the integrity and functions of local ecosystems, which are discussed in Chapters 8 and 10. For instance, the specific location of buildings within an urban core ecosystem, and within the region, is important to determine the building's current and potential influence on the biodiversity of local and global ecosystems. In addition, the state of biodiversity and ecosystem functions of local and global ecosystems influences the relative effectiveness of various building scale biodiversity goals and strategies. The following subsections review existing research findings on contextual factors that are important to consider when designing habitat patches within urban core ecosystems.

§ 11.4.1 Design for connectivity potential

The impact of a number of contextual issues are dependent on the quality of the connectivity of the site to the local ecosystems. For instance, adjacent land use and activities impact the supply and flow of nutrients, materials, and energy between habitat fragments, which affects the potential of the building site to contribute to the biodiversity of local ecosystems.[96] For example, adjacent source habitat patches and small habitat patches can improve the quality of building habitat patches, while the presence of habitat patches on the building site can simultaneously improve the quality of adjacent source habitat patches and small habitat patches, thereby generating symbiotic interrelationships. Thus, the potential of building sites to function as habitat patches is dependent on the potential connectivity of the site to urban ecological corridors and habitat patches.

Therefore, the surrounding area of the building site should be analyzed to identify the locations and connection possibilities of existing ecological corridors and habitat patches, as well as to identify important species that may be established in, or migrate through, the adjacent area. To this end, design issues that should be considered when promoting species on site are discussed in Section 11.7. Biodiversity factors of adjacent ecosystems are also important to assess, as they will help determine the biodiversity conservation potential of the local urban core ecosystem and the building. For instance, these types of assessments can help identify high value ecological corridors, reserves, and species that urban core ecosystems can help sustain.[257]

To this end, a number of performance indicators for evaluating the connectivity potential of habitat patches have been identified and evaluated in existing research. However, the effects of habitat patches and their interconnections, particularly in fragmented ecosystems, are difficult to predict, and are the subject of ongoing research investigations.[125] Therefore, the value of various performance indicators are inherently contextual, and additional performance indicators will likely be developed over time. Furthermore, connectivity between patches can be both positive and negative, depending on the context. For instance, increased connectivity between patches has been found to increase recolonization rates of species between patches, by allowing individuals to move between patches. In turn, higher recolonization rates can decrease inbreeding depression on a patch. However, it also decreases genetic differences among patches, and can transform separate metapopulations into a single population.[152] Thus, connecting individual patches is not always beneficial. Both negative and positive site connectivity factors should be assessed.

§ 11.4.2 Identify scalar issues that affect a building's biodiversity potential

Similar to the discussions of the potential impact of a building project on the functions and integrity of local ecosystems in Chapters 8 and 10, the potential contribution of an individual building to the biodiversity of local ecosystems is relatively small, in comparison to solutions developed at the neighborhood or city scale, due to a number of scalar issues, among other factors. For example, the typical available quantity of spatial environments on a building site is significantly more limited. Moreover, the available budget for an individual building, and its inherent building systems, is typically substantially smaller than municipality budgets. For example, municipalities have more resources, and vested interest, in financing infrastructure projects, performative landscapes, and green spaces. Nevertheless, building scale solutions can have potential magnifier effects that increase the value of building scale biodiversity solutions, such as promoting the growth of indigenous plants by visitors of a parkscape, as discussed in Chapter 9.

§ 11.4.2.1 Building scale design goals should focus on improving the biodiversity of the region

Furthermore, in terms of designing buildings to improve the biodiversity of local ecosystems, building scale design solutions should be focused on addressing the biodiversity goals that are most important to address at the larger regional scale, due to the issues discussed in Chapter 8. For instance, local constructed and natural ecosystems inherently have dynamic interrelationships that influence the effectiveness of biodiversity design solutions at any given location. Moreover, the impacts of constructed ecosystems on the biodiversity of local natural ecosystems, and vice versa, are dependent on the state of the natural and constructed ecosystems. Thus, regional scale biodiversity assessments, which evaluate the biodiversity of local constructed and natural ecosystems within the region, should be conducted to assess the potential effectiveness of various design solutions to promote biodiversity and mitigate the negative impacts of constructed ecosystems. Hence, it is important to assess the state of biodiversity of local and global ecosystems, in order to determine effective biodiversity goals at the building scale. Furthermore, building scale biodiversity solutions should be focused on how to maximize the potential of the building site to improve the biodiversity of the ecosystems within the local region.

To this end, the identification of the type of constructed ecosystem the building site is located within can provide a general understanding of the area's current species richness and biodiversity potential, as discussed in Chapter 8. Likewise, the identification of the types of local natural ecosystems within the region will generate a greater understanding of how the building site can improve the biodiversity of local ecosystems. However, it is important to note that specific contexts can deviate from these generalizations, partly due to the effects of the physical quality and characteristics of specific environments on the biodiversity of local ecosystems. For example, although initial research on the biodiversity of various urban areas described the rural-urban gradient as a relatively simple linear relationship, more recent research has found that cities can also be asymmetrical and polycentric, with multiple urban core ecosystems and non-linear rural to urban gradients.[257, 313] Moreover, some cities function as mosaics, with interspersed industrial, suburban, rural, and urban core ecosystems. Chapter 8 reviews the general properties of the different types of constructed ecosystems that can be found within urban areas.

§ 11.4.2.2 Consider the potential of buildings to support national and global biodiversity issues

Certain national and global biodiversity issues can be addressed at the building scale, although their effectiveness is dependent on their context. For instance, grassland plant species have been found to have the greatest decline in species population in the US. Grassland species typically are found in agricultural areas. Urban areas can provide refuge for these species.[34] Furthermore, although the introduction of non-native species may enrich local biodiversity in some cases, global species diversity can be decreased through the extinction of unique local species.[313] Therefore, in regions with rare and endangered indigenous species, it can be particularly important to provide habitat for endangered and rare species from the region, in order to slow the loss of regional biotic uniqueness and global biodiversity.

§ 11.4.3 Identify temporal issues that affect a building's biodiversity potential

Assessments of the effects of the region, individual ecosystems, and project site on the biodiversity of the region should account for projected future changes. The impacts of probable future urban developments, the effects of climate change, and other potential influential factors should be considered. Section 11.6 reviews individual habitat patch scale temporal design issues that should be considered.

§ 11.4.4 Reduce disruptions of flow + function

Habitat patches within urban core ecosystems are typically connected to highly disturbed matrices.[314] For instance, urban core ecosystems tend to impair the flow and function of species and ecosystem functions of the pre-existing natural ecosystems they are constructed on, such as by disturbing migration corridors. Moreover, habitat patches within urban core ecosystems tend to be frequently disturbed, and as a result, remain as early succession stage habitat patches. Moreover, reducing disturbances on building sites has been found to promote native species richness, promote multi-succession stage habitat patches, and reduce the vulnerability of the site to invasive species, as discussed in more detail in Sections 11.5.1 and 11.5.3.[281] Thus, in terms of promoting biodiversity, buildings should be designed to minimize disruptions to the site and adjacent sites, when early succession habitat patches are not a priority.

There are a number of design strategies that can minimize disruptions. For example, the planting strategies and landscape management practices on building sites can be designed to minimize maintenance requirements and disturbances.[412] Moreover, building sites can be designed to improve habitat continuity and species flow within the local ecosystems by providing habitat patches that connect to fragmented migration and ecological corridors, as well as adjacent habitat patches.[99] For instance, trees can form aerial ecological corridors. The roofs of buildings can contribute to aerial corridors through the provision of vegetation cover and temporary habitat patches.[391] Furthermore, it is important to note that different species tolerate different levels of human disturbance, which needs to be addressed when evaluating the connectivity potential of building habitat patches, as well as effective site disturbance mitigation strategies.[99]

§ 11.4.5 Design to overcome dispersal barriers

Existing research indicates that native species are lacking from urban core ecosystems not because of the physical characteristics of the sites themselves, but due to disturbances and the presence of various dispersal barriers between the native species' source populations and urban core ecosystems, such as artificial walls, roads, railroad tracks, large constructed and non-vegetated areas, and missing habitat patches and corridors.[57, 281, 313] For instance, Lundholm (2010) provides a review of a range of types of constructed environments and environmental conditions that have been found to be able to be colonized by species that are native to the local region in existing literature.[281] Based on these findings, Lundholm (2010) suggests that most constructed environments foster a habitat that can be inhabited by species from the local region.

Furthermore, it is important to note that dispersal barriers have been found to affect different types of species differently. For example, there is evidence that more mobile species, such as butterflies, are not substantially affected by dispersal barriers within urban areas. Moreover, in some of these cases, natural barriers have been found to substantially affect the mobile species' dispersal and migration abilities.[270] Thus, in some cases, natural dispersal barriers can be more important to assess than constructed dispersal barriers.

Therefore, it is important to identify existing dispersal barriers between source habitat patches and the building site, to determine the potential of the site to mitigate dispersal barriers, as well as to determine the habitat potential of the site. The design of habitat patches to avoid functioning as dispersal barriers is discussed in Section 11.5.

§ 11.4.6 Account for effects of typical buildings

Typical building constructions influence the biodiversity potential of ecological networks and patches in numerous ways, and should be accounted for when assessing the biodiversity potential of a building site. For instance, on-site landscapes tend to be non-porous, intensively managed, incur high maintenance costs, and have a limited variety and structural diversity of plant species and habitats.[9, 412] In addition, tall buildings can limit insect richness by functioning as dispersal barriers through their size and location within the urban core ecosystem, as well as by blocking sunlight and generating wind tunnels that impact species migration potential.[301, 426] Moreover, some building materials have been found to discourage, and in some cases negatively affect, local species populations, such as steel and glass. Negative effects, such as glass windows disorienting birds and other mobile species, need to be addressed by building design strategies.[258, 381] At the same time, some building materials, such as concrete external walls, have been found to be able to provide suitable habitat for certain species in some contexts.[281] The potential of the design of buildings to function as habitat is discussed in Sections 11.6 and 11.7.

§ 11.4.7 Connect to source + sink patches

Source habitat patches foster local species populations to ecosystems, by generating self-sustaining populations of species. The rate of emigration of species is greater than the rate of species immigration within source habitat patches.[367] A number of design factors affect the potential of a habitat patch to function as a source habitat patch, such as providing the necessary resources a species population requires, as discussed in Section 11.5.6, as well as providing an appropriate quantity of high quality space, as discussed in Section 11.5.5. Source habitat patches can be both within an urban area, such as a park, and outside of an urban area, such as a nature reserve.[257] They can be connected to individual habitat patches through various types of ecological corridors. Furthermore, it is important to note that a patch that functions as a source for one species can function as a sink patch for other species.[367]

In sink patches, species immigration rates exceed emigration rates. Sink patches tend to lack the resources that are necessary for species to survive, and therefore are low in quality and are unable to support populations of species. Interestingly, at any given time, sink habitats can have a greater population density than adjacent source patches. However, since sink patches depend on source patches to maintain their populations, the connections between sink patches and source patches must be maintained to avoid localized extinctions. Moreover, there is evidence that since different species compete for breeding sites, sink sites within an ecosystem that is comprised of both source and sink habitat patches can enhance biodiversity in some cases.[394]

§ 11.4.8 Connect to ecological corridors

The success of ecological corridors depends on the presence and quality of the habitats that are connected by the corridor.[333] Indeed, relatively close distances between patches, and connectivity between patches via corridors or stepping stone habitats, have been found to lead to high recolonization rates of habitat patches that experience high rates of species turnover.[152] Thus, the identification of source and sink patches can help identify potential high value ecological corridors that the building site can connect to and support on site. Moreover, the identification of potential ecological traps can help determine patches that should not be interconnected, as discussed in Section 11.4.17.

The width of ecological corridors can be particularly important in promoting species migration.[333] To this end, habitat patches adjacent to ecological corridors can be designed to provide additional width to corridors, by providing supplementary habitat. Moreover, habitat patches connected to ecological corridors have been found to maintain attributes of the more continuous corridor habitat, as well as support greater biodiversity.[96]

Furthermore, it is important to note that depending on the species, ecological corridors are not always comprised of continuous habitat patches. For instance, fragmented stepping stone habitats can function as ecological corridors in some cases.[96]

§ 11.4.9 Consider the biodiversity potential of constructed environments functioning as stepping stones

Although the fragmentation of habitats within natural ecosystems through human development typically reduces the biodiversity of natural ecosystems, the provision of various types of fragmented habitats within constructed ecosystems can promote local biodiversity. For instance, Bodin et al. (2007) found that the removal of small habitat patches that bridged between larger clusters of patches reduced pollination cover, and forest connectivity dropped more rapidly than in areas where small habitat patches were not present.[55] As discussed in Section 11.4.8, recolonization rates of patches that have experienced local extinctions have been found to be higher when patches are interconnected by ecological corridors or stepping stone patches.[152] Moreover, clusters of small habitat patches, such as gardens, have been found to function as effective habitat patches for some species, as discussed in Sections 11.4.10 and 11.5.5.

Within urban core ecosystems, the availability of space is typically an issue. Within this context, stepping stone habitat patches and temporary habitat patches are important to consider, as they typically are smaller than source habitat patches.[174] Thus, buildings can function as stepping stones for species to connect to larger habitats and corridors. The potential of buildings to function as stepping stones also depends on the connectivity, habitat quality, and size of the patch, among other issues. These issues are discussed in further detail in Section 11.5.

§ 11.4.10 Interconnect small habitat patches to other patches + ecological corridors

Existing research indicates that small habitat patches can be effective within fragmented ecosystems, depending on the quantity and quality of the patches. For instance, Summerville (2001) found that small habitat patches that were of high quality, in terms of providing a species' resources, such as host plants, were just as effective as larger habitat patches. At the same time, small habitat patches that were of low quality had substantially lower species richness.[426] Thus, in this case, the quality of the habitat patches was more important to the local species' populations than the size of the patch.

Moreover, clusters of small habitat patches have been found to be able to effectively support local species. For instance, in some cases, clusters of small habitat patches have been found to have more species richness than large habitat patches, when considered as a group.[441] For example, Gledhill (2008) found that the species richness of ponds was more significant with pond clusters than a single pond. Furthermore, some taxa, such as amphibians and dragonflies, require multiple habitat patches, and in some cases, the quality of the overall pond habitat network has been found to be more important than the quality of individual ponds. Thus, clusters and networks of small habitat patches can be effective components of urban core ecosystems.

However, it is important to note that the resource quality of habitat patches and clusters of patches affects the quality of the habitat patches. For instance, species have been found to move between patches to obtain critical resources, and patches in close proximity to each other have been found to be able to provide the various necessary resource requirements of a species as a group.[385] These results suggest that the effectiveness of designed habitat patches is dependent on their connection to other patches, as well as to the resources individual and clusters of patches provide. The various types of resources species require are discussed in Section 11.5.6. Therefore, when designing small habitat patches, it is important to determine which types of habitats and resources are adjacent to the site, and which can be interconnected. Furthermore, these results indicate that it is important to consider the potential of clusters of habitat patches as larger scale habitat patches, as well as ecological corridors.

Nevertheless, it is important to note that patch size has different effects for different species. For instance, small patches have more 'edge effect', which is beneficial for some species, while detrimental to others.[125] These issues are discussed more in detail in Sections 11.5.3 and 11.5.5.

§ 11.4.11 Interconnect compatible habitat patches

In terms of connectivity, Cook (2002) suggested that the ideal condition for a constructed environment is to be buffered by compatible land use types and vegetation.[99] For example, the presence of adjacent gardens has been found to increase the species richness of urban parks.[81] In addition, complementary small scale habitat patches, such as garden shrubs and ponds, have been found to increase species richness.[172]

It is important to note that compatible land use types for habitat patches can include diverse habitat types. For instance, gardens near open spaces allow some species to use the various habitats during different development stages, such as open park space for adult individuals and garden space for protecting youth.[385] Thus, the compatibility of adjacent habitat patches and corridors substantially affects their potential to improve the biodiversity of local ecosystems. However, it is important to note that the applicability of this strategy varies for different species and site conditions.

§ 11.4.12 Design for habitat diversity

A number of existing studies have found a correlation between habitat diversity and species diversity,[206, 244, 432] in support of the 'habitat heterogeneity hypothesis'.[407] Moreover, this hypothesis has been found to be particularly relevant for habitats disturbed by human communities, including within urban core ecosystems.[244, 432] To this end, buildings provide the opportunity to develop a diverse range of habitats, which can contribute to the habitat heterogeneity and species diversity of local ecosystems. Nevertheless, it is important to note that the scale of diversity is important, as discussed in Section 11.5.7. Moreover, the diversity of habitats within an urban core ecosystem should be identified, in order to determine potentially effective interconnections that can be made between habitats, and to better understand the resources and habitat types that currently exist within the urban core ecosystem.

§ 11.4.13 Generate multiple connections + patches in urban areas

It is important to note that local extinctions and recolonizations of habitat patches are common in nature. Thus, it is important to have a diverse network of patches that are interconnected in multiple ways, in order to ensure the resilience of natural and constructed ecosystems.[152] For instance, multiple ecological corridors between source habitat patches are important to sustain their quality. By having diverse connections between high quality patches, more opportunities for species dispersal are generated, such as through connections to temporary and sink habitat patches.[385] Moreover, the generation of greater connectivity through the development of diverse ecological corridors and connections also reduces the risk of creating habitat sinks.[85] Thus, it is also important to generate multiple source habitat patches, in order to maintain the long term resilience of local species populations.

§ 11.4.14 Determine effective distances between constructed environments + adjacent patches

There is evidence that the quantity of interactions between habitat patches increases as the distance between patches decreases, as well as when the quantity of area of both patches increases.[385] Moreover, recolonization rates have been found to be high when patches are close together.[152] However, it's important to note that there are positive and negative effects to interconnecting patches, and the specific context and biodiversity conservation goals will dictate effective solutions. For instance, greater connectivity between patches can also increase competition between species, which can be negative or positive for both species, depending on the context.[394]

§ 11.4.15 Design for species' dispersal distances + home ranges

An animal's home range is the area which it regularly traverses in search of food or breeding partners. In some cases, individuals move to a new range. The average distance of these one way movements to a new range are referred to as dispersal distances, and are more common in juveniles. It is important to note that dispersal distances vary substantially within the same species. Furthermore, within a population, the majority of animals move short distances while a few tend to make long distance movements.[331] Although there has not been much research conducted on dispersal distances, particularly in urban core ecosystems, existing research indicates that there is a linear relationship between home ranges and dispersal distances.[389]

The dispersal distance and home range of species have been used in existing studies to estimate the potential connectivity of habitat patches to source patches and corridors. This is achieved by using existing research on the dispersal distance and home range of specific species to estimate the maximum distance species will travel between patches, as well as to acquire necessary resources. To this end, Table 11.1 lists the dispersal distances and home ranges that have been found for several species in existing literature. As a general guideline, species migration reduces as the distance to a new patch from a source habitat patch increases.[385, 410] Thus, it is important to consider the dispersal distance and home range of local species when assessing the connectivity potential and general biodiversity performance of the building site.

§ 11.4.16 Consider the potential adaptability of species to urban conditions

It is important to note that although the minimum patch size and travel distance between patches for animal migration in urban areas has received relatively little research attention,[174, 389] a number of species have been found to adapt to a variety of constructed and natural fragmented habitat conditions and barriers. For instance, Koprowski (2005) found that some squirrel species' home range increased with fragmentation, Harris (1986) found that fox populations in Britain adjusted their feeding habits in towns and cities,[197] while Dover (2009) found pollinators were able to effectively use clusters of small habitat patches in fragmented ecosystems.[125] Therefore, it is possible that the minimum habitat quality and size requirements for species in constructed ecosystems may be less than the habitat requirements that have been found in existing literature for different species in natural ecosystems, as the examples cited in this subsection suggest. Nevertheless, further research on species dispersal distances and home ranges is necessary to better understand how to develop effective ecological corridor and patch systems within constructed ecosystems. An overview of existing research findings on animal dispersal distances is illustrated in Table 11.1, as a conservative guideline to provide an initial understanding of minimum dispersal distance requirements for various species.

§ 11.4.17 Identify ecological traps

Particularly in environments disturbed and/or constructed by human communities, there is growing evidence that some habitat patches can function as ecological traps.[36] An ecological trap is a habitat that cannot sustain a population, is low in quality in terms of reproduction and survival, but is perceived by species as either equal or greater in quality than other available, higher quality habitats. In contrast, a sink habitat patch is a habitat patch that animals settle in only after their preferred habitat, a higher quality source patch, is full. Thus, a key difference between habitat sinks and ecological traps are that animals avoid sink habitat patches when possible, while animals do not avoid, and in many cases prefer, ecological traps.[36]

§ 11.4.17.1 General types of ecological traps

Unfortunately, further research is necessary to comprehensively understand when ecological traps are created, and how to avoid generating them.[36] Nevertheless, extant literature has identified a few key issues. For instance, existing literature indicates that ecological traps can occur in diverse habitats, with and without direct human disturbance. Furthermore, existing literature suggests that animals mistakenly perceive the environmental cues of ecological traps to be of higher or equal quality as other, actual higher quality habitat patches for a variety of reasons. To this end, the results of existing literature indicate that these false perceptions are typically generated due to two general types of habitat alteration: the quality of habitat patches are reduced in imperceptible ways that makes them unsupportive of species populations, and the attractiveness of low quality patches are increased, such as by mimicking the attractive cues of higher quality patches.[171, 381]

§ 11.4.17.2 General effects of ecological traps

Theoretically, the existence of an ecological trap will cause a local population to become extinct, as animals move from higher quality habitat patches to poor quality ones. Robertson (2013) reviews a number of ways ecological traps can negatively affect a species' fitness. For instance, ecological traps can increase the risk of predation of adult or young animals by promoting a novel or modified distribution of animals within the habitat patch, providing an increased abundance of species or predators, promoting the occupation of the patch by inappropriate mating partners, reducing the availability, suitability, or quality of prey, increasing inter-animal competition for food, or providing abiotic conditions that are inappropriate for the development of young animals.[381]

§ 11.4.17.3 Urban ecological trap design issues

Moreover, habitat patches within constructed ecosystems and/or affected by anthropogenic disturbances, can negatively affect species' fitness in a variety of ways. For instance, animals must expend energy to migrate to a site. Thus, the survivability of animals that are attracted to a low quality site, but then try to migrate to another higher quality habitat patch to survive, is reduced by decreasing the quantity of available energy the animal has to migrate, defend itself, and search for resources, among other factors. Moreover, the siting of constructed environments at substantial distances from ecological corridors can negatively affect the survivability of animals in a number of ways. For instance, the location of a habitat patch adjacent to a dangerous corridor or barrier, such as a roadway, increases the mortality rates of animals migrating to and from the site.[153] In addition, animals can be confused about how to migrate from one habitat patch to another if the connection to other patches is unclear, dangerous, or convoluted. Similarly, a number of anthropogenic activities have been found to alter environmental cues in ways that make lower quality habitats be perceived as equally or more attractive than higher quality patches.[381] For instance, human disturbances can interfere with animals' interpretation of cues, such as muffling important noises or interfering with the reception of various environmental cues.[82] Thus, poor-quality constructed environments that mimic characteristics of better quality habitats can function as ecological traps.[171]

§ 11.4.17.4 Severity of ecological traps

Different ecological traps have varying levels of severity. Ecological traps that are more effective at attracting species can be considered to be more severe traps, as they are more likely to reduce species populations by attracting animals away from high quality habitats. Similarly, ecological traps that are equally preferred to high quality habitats can be considered to be less severe.[381] Classifying the severity of ecological traps can help assess which ecological traps are most important to mitigate, as well as to avoid when developing ecological corridors.

§ 11.4.17.5 Factors that affect species susceptibility to ecological traps

The susceptibility of species and individuals to ecological traps can be influenced by a variety of factors, sometimes in predictable ways. For example, historically, if poor habitat selection for a species does not strongly affect the species' fitness, than that species can be more likely to migrate

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to poor habitat patches and ecological traps. In addition, ecological traps can be attractive to specific age groups, sexes, or during certain conditions. For instance, bolder animals are more likely to avoid warning cues and inhabit more dangerous habitats. Lower condition animals that have less access to high-quality food and habitats also tend to be more susceptible to ecological traps.[381] Moreover, individual animals can be influenced by other animals, such as by following them into a trap, or by being prevented from entering a trap because it has already been filled by others.[210]

§ 11.4.17.6 Design strategies to improve or eliminate ecological traps

A number of design strategies for improving the quality of ecological traps, alleviating their effects, and eliminating them altogether have been identified in existing literature. Robertson (2013) suggests that the various strategies that have been found and proposed can be categorized into two general methods: reducing the attractiveness of falsely attractive resources and patches, and increasing the fitness value, or quality, of low quality habitat patches. The attractiveness of an ecological trap can be reduced by removing attractive cues, such as by removing resources of target species, adding repulsive cues, such as by designing ecological traps to be perceived as less desirable to target species, limiting access to traps, designing ecological traps to discourage the presence of important species and predators, increasing the connectivity between high quality patches, as well as sinks. In addition ecological corridors can be designed to be far away from ecological traps, and design teams can avoiding connecting ecological traps to ecological corridors. Methods to improve the quality of ecological traps depend on the types of species the habitat attracts. However, it is important to note that strategies to improve the quality of ecological traps tend to be similar to habitat restoration techniques, and thus can be effective ecological trap mitigation strategies in some cases. Furthermore, there is evidence that strategies that combine both methods of ecological trap mitigation may be more effective than singular mitigation strategies.[381]

§ 11.4.18 Identify undervalued habitat patches

In contrast to ecological traps, undervalued habitat patches are high quality patches that are missing the necessary cues that encourage settlement by animals.[171] For instance, a minor change can make a habitat less appealing to animals. In addition, harmless elements of human development, such as scarecrows, may function as erroneous indicators of risk that discourage settlement of high quality habitats. Moreover, harmless forms of human disturbance may also be perceived as dangerous. For example, nesting woodlarks were found to avoid areas adjacent to recreational footpaths, even though the pedestrians posed little risk to the animals.[291] Similar to ecological traps, further research is necessary to determine the types of habitat qualities that can promote the development of undervalued habitat patches. For both ecological traps and undervalued habitat patches, further research into the cues that species use to estimate the suitability of sites may generate a greater understanding of how ecological traps and undervalued habitat patches are perceived incorrectly.[171] Gilroy (2007) reviews a number of cues that have been found to influence various species' habitat selection processes.

§ 11.4.19 Physically isolated patches

In general, the greater the distance a habitat patch is from other patches, the more isolated it becomes, and therefore the less effective the habitat patch becomes at contributing to the biodiversity of local ecosystems.[99] Moreover, suitable habitats are sometimes unused when they are too physically isolated from ecological corridors and source habitat patches.[36] Nevertheless, physically isolated patches can potentially function as habitat patches. For instance, mobile species can access physically isolated patches, depending on their dispersal and home range, as well as habitat quality, among other factors. Since urban core ecosystems are dynamic, adjacent patches and corridors may exist in the future, and therefore the patch can be designed to contribute to the biodiversity of local ecosystems in the future, such as by functioning as a stepping stone patch for a future ecological corridor, or by functioning as a gene bank, as discussed in Section 11.5.12. However, it is also important to ensure that an ecological trap is not developed, as discussed in Section 11.4.17. Furthermore, it is important to note that in contexts where the building project is biologically isolated, design for ecological awareness and ecosystem functions typically become more important to address.

Thus, the potential of building sites to function as habitat patches is dependent on the potential connectivity of the site to urban ecological corridors and habitat patches. Habitat patch isolation is typically measured in one of two ways in existing studies: as the total quantity of suitable habitat within a certain radius of a patch, or, as the shortest distance to a larger patch that might serve as a specie's habitat source patch.[152]

§ 11.5 Habitat patch design issues + solutions

The quality of habitat patches, in terms of biodiversity, is dependent on a number of factors, including specific habitat and species issues. To this end, a number of performance indicators for a variety of habitat types have been identified in existing literature.[99, 152] Nevertheless, it is important to note that in many cases, further research is necessary to effectively evaluate habitat patch performance in terms of biodiversity, particularly the specific effects and functions of habitat patches within urban core ecosystems.[257] The following subsections present a range of individual habitat patch scale issues that have been found to be relevant to the design and evaluation of the quality of constructed environments within urban areas, in terms of their potential to contribute to the biodiversity of the local ecosystems.

§ 11.5.1 Degree of patch naturalness + disturbance

The naturalness of a patch is a measure of how much the patch has been disturbed by human activities.[99] Typical habitat patches within urban core ecosystems are highly disturbed, because typical maintenance practices remove leaf litter, woody plants, and other microhabitats of natural communities. These activities reduce the quality and area of habitats.[426]

Different species tolerate different levels of human disturbance. For example, in some cases, non-native plant species have been found to be able to adapt more quickly to areas of disturbance than native species.[257] In addition, a number of interior species tend to prefer habitat patches that are not as disturbed by humans as edge habitats, and a number of species have been found to actively avoid patches that are disturbed and/or lack an interior habitat, as discussed in Section 11.5.3. Furthermore, different types of disturbances, such as noise, air, soil, and water pollution, disturb different species at different rates. Thus, it is important to assess the habitat requirements of the local species to determine the effectiveness of the design of individual habitat patches. Moreover, further research is needed to determine the limitations of individual constructed environments, and urban core ecosystems as a whole, in providing habitat for various species.

From a design perspective, the level of human disturbance (and interaction) of building occupants within a building project can be categorized in the following general categories: occupation, observation, and isolation. *Isolation* interactions occur when the habitat is physically inaccessible by people. *Observation* interactions occur when people are able to access viewing areas that are *within* the habitat space, but only at the periphery of the space. *Occupation* interactions occur when people are able to freely move within the habitat space. Of course there are degrees of finer interaction differences within these general categories, such as the degree of interaction of occupants with the habitat patch. For instance, solely visually interacting with a patch via isolated views compared with walking through a habitat patch, or actively interacting with the patch. In addition, when assessing the naturalness of a building habitat patch, contextual human disturbances, such as air and noise pollution, need to also be considered.

Design strategies can minimize the degree of disturbances that impinge on habitat patches. For example, vegetation along an observation deck can reduce the visual and acoustic effects of human disturbances. In addition, the acoustic design of the space can be designed to minimize the noise transmission of observers into the habitat patch.

§ 11.5.2 Degree of boundary permeability

The *boundary permeability (porosity)* of a habitat patch depends on the available connections of the patch to other corridors and patches within the urban core ecosystem. Generally, increased porosity and connections increase the extent and rate of flows across patch boundaries.[96] As discussed in Section 11.4, the quality of the connections and adjacent patches, habitat structure, and intensity of human activities, among other factors, influence the degree of permeability and flows across the patch boundaries. To this end, potential connectivity disruptions are discussed in more detail in Section 11.4. Furthermore, the types of species and habitat influence the porosity of the patch, as discussed in Sections 11.6 and 11.7.

§ 11.5.3 Degree of edge versus interior

The qualities and biodiversity conservation potential of habitat patches differ within the areas of individual patches. For instance, the edges of habitat patches are inherently more influenced by adjacent site conditions, and orientation. For example, forest habitat edges tend to have higher temperatures, lower relative humidity, and higher wind velocities and light levels.[345] Moreover, south facing edges of habitat patches are typically warmer, drier, and wider than north facing edges, in the Northern hemisphere. There are also typically more xeric and pioneer species along the edge, as well as more shrub and herbaceous species.[96] In addition, the shape of the habitat patch also affects the quantity of edge of a habitat patch, as discussed in Section 11.5.10. It is also important to note that habitat patches without similar adjacent land use types and vegetation have an increased edge effect, thereby reducing the interior area of the patch.[99]

Perhaps more importantly, the edges of habitat patches tend to be substantially more disturbed by human activities. Furthermore, habitat patches with high levels of disturbance, such as patches with high ratios of edge area, have been found to negatively influence the types and quantities of species that inhabit habitat patches, as discussed in Section 11.5.1. For instance, ecosystems that lack interior habitat patches tend to be less able to support a number of species that prefer interior habitat, including core, rare, and endangered species.[96, 310] To this end, existing literature indicates that habitat patches within urban areas tend to have relatively low quantities of interior habitat area, in comparison to natural ecosystems.[75, 257, 385] It is important to note that the absence of certain species in urban areas, particularly species that are averse to edge habitats, such as a number of megavertebrates, have substantial, complex effects on the trophic dynamics of urban areas, as discussed in Section 11.2.6.2.[139] These effects should be considered when assessing the potential biodiversity performance of urban areas and constructed environments.

However, the critical size of patches considered necessary to foster interior environment in urban areas has not been studied extensively, and depends on the context. To this end, a literature review by Collinge (1996) found that the 'edge effect' of habitat patches may extend from the habitat edge to 8 to 15 meters into the habitat interior, and in some cases, much more.[96] Moreover, minimum habitat patch sizes that foster interior environment have been found to range from 0.8[166] to 3.0 ha[67] in existing literature. However, it is important to note that the minimum quantity of patch size needed to provide interior habitat area has been found to vary by ecosystem and species type, as well as depend on a number of spatial qualities, such as edge/surface area ratio and naturalness.[96, 310] For instance, as discussed in Section 11.4.16, there is evidence that some species adjust their behavior within urban areas. This finding suggests that some species may be able to be sustained in smaller habitat patches, and smaller interior areas within habitat patches, than typically required in natural environments. This issue is discussed in more detail in Section 11.5.5. Therefore, further research is necessary to determine the potential effectiveness of constructed environments to foster interior habitat area for a diverse range of ecosystem and species types. Furthermore, it is important to note that human activities typically disrupt the interior of habitat patches in urban areas, thereby affecting the quality of the habitat patch, including its biodiversity conservation potential. For example, suburbanites have been found to travel up to 82 m from home for regular outdoor recreation activities.[96]

In terms of building design, the results of existing literature indicate that typical mid-size commercial office buildings are unable to foster interior habitat for a range of species, because of the limited spatial area that is available on these sites. Nevertheless, constructed environments may be able to function as stepping stone habitat patches and temporary habitats for interior species with source populations and migratory routes in nearby patches and corridors, as discussed in more detail in Section 11.5.5.

§ 11.5.4 Design for species diversity

Species diversity is important for sustaining local ecosystem functions. For instance, in general, the more ecosystem functions that are provided, the more species diversity is necessary to sustain them.[455] Moreover, species diversity with diverse functions may buffer ecosystem processes and their services, and make ecosystems more resilient.[103] However, the value of species diversity and specific species populations to providing ecosystem functions is inherently contextual, and currently under debate, particularly within urban areas.[20, 391, 455] Chapter 10 discusses this issue in more detail. Nevertheless, habitat patches within buildings, such as gardens and green roofs, have been found to improve native species richness.[174] Thus, building environments can positively contribute to species diversity, although the types of species building environments can promote is context and scale dependent. Furthermore, care should be taken to consider the types of species that are attracted to specific types of habitats and contexts, in order to avoid the generation of ecological traps.

§ 11.5.5 Effects of habitat patch size

The relative size of a habitat patch influences the ways in which it can contribute to the biodiversity of local ecosystems. Thus, a current method for calculating the quality of a habitat patch uses the size of each habitat type to evaluate its quality.[125] For instance, existing literature indicates that vegetated areas of less than approximately 1.0 ha typically cannot support self-sustaining habitat patches for a number of species, particularly those that prefer to inhabit the interior areas of habitat patches, such as megafauna, as discussed in Section 11.5.3.[67, 166, 411] For example, Warren (1992) found that habitat patches had to be at least 1 ha to function as a source habitat patch for various species of butterflies.[471] Nevertheless, habitat patches as small as 0.3 ha have been found to effectively function as habitat patches for a variety of species, particularly mobile species, even within urban core ecosystems.[125, 174, 301, 385, 411] To this end, the minimum habitat patch sizes that several individual species have been found to inhabit are shown in Table 11.1. Moreover, a review of existing literature by Rudd (2002) of minimum size habitat patches for several species that have been found to occupy urban areas, including tawny owls and voles, found that half a hectare was an appropriate minimum habitat patch size that would ensure the patch would be utilized by a number of local species.[385]

However, it is important to note that, particularly within urban areas, individual habitat patches tend to be smaller than existing literature indicates is necessary to generate source habitat patches, as discussed in Section 11.5.5. Moreover, minimum suitable habitat patch sizes differ by species, ecosystem type, the quality of the patch, resources available within the patch, as well as a number of other contextual factors. In other words, a patch that is smaller but provides more resources than a larger habitat patch can be higher in quality, and better foster self-sustaining species populations, despite its size. In addition, the types of resources habitats should provide to foster self-sustaining populations are discussed in Section 11.5.6. However, as discussed in Section 11.4.16, it is important to note that the adaptability of a range of species to urban conditions suggests that some species can adapt to smaller habitat sizes than existing literature on minimum habitat sizes for species in natural habitats indicates. In addition, existing literature has found that various species react differently to a given set of habitat conditions. For instance, some species may be more sensitive to habitat patch size and habitat edge/interior ratios, particularly less mobile species. To this end, further research into suitable habitat conditions for various species and habitat types is necessary. Nevertheless, the following subsections discuss the potential of small habitat patches, particularly at the building scale, to contribute to the biodiversity of local ecosystems.

Species	Dispersal distance/home range	Minimum inhabitable patch size
Small mammals	1km^2 [43]	2.3 ha, to have interior environment[310]
Bees	900m^2 [54] ; med. size bees: 1-2 km[301]	<0.1 ha[54]
Tawny owl	12-24 ha [376]	0.3 ha[376] **core patch**
American robin, common yellowthroat, gray catbird		<0.3 ha[380]
Bank vole		<0.3 ha[456] **presence**
Townsend vole		0.18 ha[196]
Ground arthropods	1 km[338]	
Great or northern crested newt	1 km[172]	
Butterfly	<2km[411]	0.3-0.62 ha[301, 411] ; 0.5 - 1.0 ha for local population of various butterfly species[411]
Wind dispersed plants	<200 m[152]	n/a
Animal dispersed plants	Typically dropped at patch or corridor edges, dispersal decreases with distance, depends on animal movement[152 343]	n/a

TABLE 11.1 Minimum inhabitable patch size and dispersal distance for various species found in existing literature

§ 11.5.5.1 Biodiversity potential of small habitat patches

Habitat patches that are too small to function as source habitat patches can still contribute to the biodiversity of local ecosystems in different ways. For instance, small habitat patches can function as stepping stones and temporary habitat patches, as discussed in Section 11.4.9, or as part of a clustered habitat, as discussed in Section 11.4.10. In particular, microhabitats, or habitats that are smaller than typically defined small habitats for a given species, can function as part of a cluster of small habitat patches. For instance, residential gardens, although much smaller than typically defined small habitat patches for butterflies,[301, 411] have been found to function as part of a clustered source habitat patch.[28, 40]

Moreover, within fragmented ecosystems, small habitat patches have been found to be integral to the functions and biodiversity of ecosystems in a number of studies. It is important to note that extant research on effective habitat patch sizes are typically conducted in fragmented forests and negatively performing urban areas.[174] Thus, further research into the effectiveness of urban areas and constructed environments that are designed to foster self-sustaining populations and positively contribute to local ecosystems is necessary to adequately evaluate the potential of urban areas and constructed environments to promote biodiversity, as well as to generate effective building and city scale biodiversity design guidelines. Nevertheless, existing findings from research conducted in fragmented forests can function as a conservative guideline. For instance, the removal of small bee habitat patches reduced the functionality of ecosystem services by 36% within a fragmented forest ecosystem.[54] In addition, by removing small habitat patches that connected larger clusters of patches, pollination cover and forest connectivity was further reduced within the fragmented forest ecosystem.[55]

§ 11.5.5.2 Influence of habitat patch quality on the performance of habitat patches, in terms of biodiversity

The quality of habitat patches has been found to affect the minimum patch size requirements of several species in existing literature.[310] For example, small patches with higher quality habitat and more flowers were visited more by butterflies and skippers than large patches with lower habitat quality and less flowers.[426] In addition, Summerville (2001) found that habitat quality may be as important as habitat loss in maintaining species diversity.[426] In a separate study, the quality of a habitat patch was found to be one of the most important factors that affected butterfly species richness within various habitat patches.[125] Furthermore, a review of existing literature by Goddard (2010) found that gardens smaller than typically cited minimum patch sizes for butterflies were found to support diverse butterfly species.[174] Therefore, the results of existing literature indicate that the quality of small habitat patches, such as increased vegetation cover and structural diversity, has the potential to make up for the limited area of small habitat patches. To this end, the types of qualities that affect the quality of habitat patches are discussed in more detail in Section 11.5.6.

§ 11.5.5.3 Influence of habitat patch size on the biodiversity potential of buildings

Taken together, these results suggest that building scale habitat patches can positively contribute to the biodiversity of local ecosystems. However, it is important to note that building scale habitat patches are generally smaller than typically classified small habitat patches for a number of species, and thus are smaller than minimum inhabitable habitat patch sizes for a range of species. Thus, building scale habitat patches will tend to function as microhabitats, thereby functioning as temporary habitats, stepping stone habitats, and ecological corridors for important species. For instance, residential gardens in the UK have been found to provide valuable habitat to declining, nationally important bird species.[75] In addition, Section 11.6.4 reviews additional existing research findings on the potential of buildings to function as habitat patches. Therefore, due to the small area potential of typical building projects, the size of habitat patches at the building scale should, as a general guideline, be maximized, and care should be taken to maximize the quality of building scale habitat patches.

§ 11.5.6 Design for resource provision

High quality habitat patches promote species' fitness by providing the resources necessary to sustain species populations.[367, 381] Generally, species require spatial environments that provide effective opportunities to attract and breed with mates, raise young, and acquire food and water. In addition, species also require shelter and nesting areas. However, it is important to note that the value of individual habitat patches is inherently interconnected with, and influenced by, the other habitat patches within the local ecosystems. For instance, the regional diversity of habitats, as well as proximity of adjacent habitats, may be of equal or greater influence on species diversity and abundance within a given habitat. Indeed, Section 11.5.7 discusses the potential of clusters of small scale habitat patches to provide complementary resources. Moreover, a given resource for one species, such as perches for predatory birds, may limit the resources of other species, such as adequate shelter and foraging environment for bird prey species.[367] Thus, the particular resources and habitat types that maximize the quality of the individual habitat patch are not simply the provision of every resource for a given species, but must be determined based on the needs of the multiple species within the local ecosystems, as well as the quality of the interconnected habitat patches within the local ecosystems.

§ 11.5.7 Habitat patch structure: design for diversity

The structural characteristics of natural ecosystems have been found to have a large impact on ecological processes when the proportion of the ecosystem covered by natural habitats is below 10-30%.[55] Similarly, less than 30% of typical urban core ecosystems are covered by natural habitats.[82] Within fragmented ecosystems, heterogeneous conditions, such as diverse temperature, topography, soil types, structure types, and habitat types have been found to increase species richness and abundance. Conversely, loss of habitat heterogeneity tends to negatively affect species richness in fragmented ecosystems.[9, 96] Moreover, existing literature suggests that species may be less susceptible to local extinction in heterogeneous fragmented ecosystems, compared to more homogenous fragmented ecosystems.[17] Specifically, the structural diversity of habitat patches has been found to have a significant impact on their conditions and functions. For instance, the provision of structurally diverse habitat patches has been found to foster greater species richness, abundance, and ecosystem functions within fragmented ecosystems.[174] Thus, the structure of habitat patches contributes to their quality. Moreover, in terms of promoting biodiversity within local ecosystems, it is important for habitat patches to foster structural diversity throughout the local ecosystems. To this end, the structural diversity of vegetation within an ecosystem or habitat patch can be assessed by evaluating the area covered by each different layer of vegetation within the patch or ecosystem, such as vines, trees, and shrubs, as discussed in Section 11.5.9.[99]

Small habitat patches, such as at the building scale, can be designed to contribute to the structural diversity of local ecosystems through two general design strategies. Small scale habitat patches can provide habitat patches that are structurally diverse from other habitat patches, and small scale habitat patches can contribute to the structural diversity of a cluster of small adjacent habitat patches. In other words, small scale habitat patches can be designed to provide structural diversity to local ecosystems at two different scales. For instance, Dover (2009) found that individual small habitat patches do not have to be designed to provide every resource that species require in order to function as a high quality habitat. Rather, small habitat patches can complement the resources available in adjacent patches, by functioning as part of larger habitat patches. To this end, large habitat patches can be comprised of adjacent small habitat patches that together provide the necessary resources for a species population.[23] From this perspective, individual small habitat patches may in some cases have less structural diversity than larger habitat patches, and still positively influence the local ecosystems. For instance, the structural diversity of an individual small habitat patch may be low, and yet may provide a structure type that would otherwise be absent in the the overall structural diversity of a cluster of small habitat patches.

The most appropriate strategy depends on the context of the building project, such as the potential size of the building habitat patches, the type and quality of adjacent habitat patches, and the current level of structural diversity within the urban core ecosystem. However, further research is needed to determine the effectiveness of multiple, complimentary and non-complementary building scale habitats. Moreover, one of the primary factors affecting the structural diversity of habitat patches is the vegetation cover, which is discussed in more detail in Section 11.5.8.

§ 11.5.8 Design for vegetation cover

Vegetation cover, the proportion of ground surface covered by vegetation, has been found to be an important component of habitat quality.[99] For instance, vegetation has been found to be an effective predictor of birds, mammals, amphibians, reptiles, and insects within urban areas.[314] Nevertheless, it is important to note that the quality of vegetation cover directly affects the performance and quality of habitat patches, in terms of biodiversity. For example, existing literature suggests that the structural diversity of vegetation within a habitat patch has a greater impact on species diversity than the diversity of plant species within a habitat patch.[286] Thus, it is important to design for, and evaluate, the structural diversity of vegetation within individual habitat patches.

§ 11.5.8.1 Design for diverse layers of vegetation

To this end, the possible types of vegetation that are present in habitat patches can be categorized into layers based on their vertical location within the habitat patch: tree canopy , understory, and ground cover, as illustrated in Figure 11.2. Furthermore, it is important to note that the structural composition of the vegetation layers of a habitat patch directly impacts its conditions and quality. For example, trees provide shade and cool the microclimate within the habitat, while providing aerial canopy shelter structure and reducing solar radiance. Similarly, floral diversity and the three dimensional structure (complexity) of garden vegetation provide diverse habitat resources, and have been found to be an important predictor of vertebrate and invertebrate abundance and diversity.[174]

FIGURE 11.2 Vertical vegetation layers typically employed in ecosystem structural diversity analysis

§ 11.5.8.2 Methods to evaluate the quality of vegetation cover

Current research methods calculate the area covered by each layer of vegetation within the patch or ecosystem, such as vines, trees, and shrubs, to generate an estimate of the habitat's structural diversity. This metric, as well as the proportion of vegetation cover and native vegetation within a habitat patch, have been used to indicate the quality of a habitat patch.[99] However, the quantity of native vegetation is not always a reliable indicator of habitat quality, as discussed in Section 11.7.1. Moreover, it is important to note that the optimal amount and type of vegetation cover for a given habitat depends on the habitat type and habitat requirements of the species that the habitat patch is being designed to accommodate. Therefore, a standard vegetation cover metric can provide a rough estimate of the quantity of vegetation cover of a habitat patch. However, this quantitative metric should be paired with quality metrics, such as the performance parameters discussed at the beginning of this subsection, in order to effectively determine the performance of the habitat patch, in terms of contributing to the biodiversity of the local ecosystems. To this end, further research is necessary to determine the specific relationships between the quality and quantity of vegetation cover in constructed environments.

§ 11.5.8.3 Identifying the typical state of vegetation cover within urban areas

Several generalizations of the state of vegetation cover within urban areas have been found in existing literature. For instance, species richness for a variety of species tends to be higher in parts of urban areas that are more vegetated, and lowest in urban core ecosystems, where vegetation cover is minimal.[314, 391] However, it is important to consider that this may also be due to other confounding factors, such as dispersal barriers, as discussed in Section 11.4.5. Moreover, in terms of building program, commercial and industrial areas tend to have less species richness than residential areas. This is partly because residential areas tend to be comprised of individual landscapes, in which the residents are more apt to plant diverse vegetation than in commercial areas. On the other hand, the landscapes within commercial areas, such as business and industrial parks, are commonly developed as a single plan. Moreover, landscape designers tend to plant a limited number of favored species for their projects, thereby limiting the potential of the sites to provide structural diversity.[362, 412] Thus, in order to promote the biodiversity of local ecosystems, the design of constructed environments should be reconsidered to take into account ecological design factors, such as vegetation cover and structural and habitat diversity.

§ 11.5.9 Design for leaf litter

The presence and decomposition of leaf litter is an important determinant of the quality of habitat patches. The decomposition of organic matter provides organic nitrogen, which promotes vegetation growth. In addition, decomposition provides heavy metal site filtration, determines ecosystem nutrient flow and availability of resources for higher plant communities. Decomposition also provides habitat and resources for fungi, bacteria, and invertebrates.[308, 443] Furthermore, designing site landscapes to retain leaf litter reduces site maintenance costs, as well as physical human and pollution disturbances on site. In terms of measuring performance, slow decomposition rates indicate high performance.[308]

§ 11.5.10 Habitat shape + orientation

There is limited existing research on the effects of the form of a patch on its biodiversity conservation potential. For instance, several studies have found that some bird species prefer elliptical patches within natural environments. Moreover, Pfenning (2004) found that elongated patches oriented perpendicular to the direction of species dispersal receive more migrants.[361] However, this preference was only found to be true for animals moving in one direction, such as migratory animals and animals moving along unidirectional corridors. This preference was not supported for random direction movement, or movement when there was long distances between patches or high dispersal or movement rates.[96, 361] Furthermore, it is important to note that patches that are more elongated along one axis, i.e. with a higher edge/surface area ratio, have a higher proportion of edge habitat.[310] Thus, there is evidence that habitat shape and orientation are important design factors to consider when designing habitat patches. However, further research into the impact of form on habitat quality and function, for a variety of species and ecosystem types, is necessary.

§ 11.5.11 Maintenance capacity

The maintenance capacity of a habitat patch is the potential of a habitat patch to be managed by people in ways that sustain the ecological flows of the local ecosystems.[132] Therefore, a site that has a positive maintenance capacity has a positive effect on the local ecosystems, while a site that has a negative maintenance capacity has a negative effect on local ecosystems. As discussed in Section 11.6.2, low nutrient habitat patches tend to be uncommon in urban areas. Moreover, low nutrient ecosystems tend to require less active maintenance, which reduces habitat disturbance. For instance, a building landscape area that is maintained as a meadow or grassland can typically be cut once per year to maintain the habitat as a low nutrient grassland habitat.[75] Thus, this type of habitat patch can have a positive maintenance capacity. On the other hand, a site area that is paved results in the destruction of the local soils and vegetation, as well as reduces groundwater recharge.[425] Thus, a paved site area has a negative maintenance capacity. Furthermore, it is important to note that the type of habitat and species, as well as the connectivity of the patch to other habitat patches and corridors, affects the maintenance requirements of the habitat patch.

Moreover, it is important to note that active maintenance within small habitat patches can be beneficial. For instance, the maintenance of habitat patches within a nature reserve to sustain local populations of rare and endangered species tends to be cost intensive and difficult to maintain, due to the size and dynamic qualities of these patches, as discussed in Section 11.6.1.[299] Buildings and urban landscapes can supplement these areas, by providing actively managed, smaller scale habitat patches. Depending on the design strategy, maintenance costs can be comparatively lower, by incorporating the maintenance of the habitat patch into the existing maintenance regime of the building or site, as well as through the incorporation of building and municipal infrastructure systems. Moreover, building integrated habitat patches can provide wildlife rehabilitation, captive breeding, and gene banks, among other active maintenance ecological programs. The potential of incorporating actively maintained habitat patches on building sites are discussed in the next subsection.

§ 11.5.12 Building as gene banks

The development of urban areas typically results in the removal of indigenous species, through habitat loss and transformation, as discussed in Section 11.7.1, as well as negatively affects the biodiversity and ecosystem functions of adjacent natural ecosystems.[257] Furthermore, it is important to note that local extinctions and recolonizations are common in nature, from none to about half of the patches of an ecosystem a year. Therefore, it is important for ecosystems to have source habitat patches that promote the recolonization of patches that have experienced local extinctions.[152]

To this end, buildings can promote the preservation of native species by functioning as gene banks for indigenous flora and fauna. For instance, indigenous species that are displaced by human disturbances within and around urban core ecosystems can repopulate an area if they are reintroduced to the site, such as through various dispersal methods from a building gene bank.[425] Moreover, building habitats provide unique opportunities to provide a variety of controlled and uncontrolled climate, soil, and nutrient conditions for rare, indigenous species. In addition, flora and fauna within building habitats can be actively managed relatively easily, in comparison to actively managing a large nature reserve. For instance, management practices, such as irrigation, can be generated through automated systems, and existing building maintenance staff can incorporate active maintenance into their existing maintenance schedule and operations.

Building scale gene banks can be designed to distribute native species within urban areas. For instance, when there are adjacent habitat patches, the seeds from vegetation species grown on buildings can be distributed throughout the urban area, and potentially adjacent natural ecosystems, via local wind flows and animal dispersal processes. When a building is disconnected from local habitat patches, the flora and fauna of building gene banks can aid the repopulation of local ecosystems and adjacent habitat patches, depending on the context. Moreover, if isolated sites can be connected to the ecological network of the urban area in the future, such as through the resolution of human disturbances and other dispersal barriers, or the development of an ecological corridor, then isolated sites can function as temporary gene banks, much like some zoos attempt to function as temporary refuges for typically high profile endangered species.[134] Furthermore, it is important to note that buildings provide the opportunity for repopulation, both locally and through a potential magnifying effect, by creating opportunities for inhabitants to interact with flora and fauna, and thereby promote the value and potential further growth of these species, as discussed in Chapter 9. To this end, existing greenhouses and zoo habitats can potentially be designed to function as gene banks. Moreover, they provide case studies of existing examples that can be used to help develop effective building scale gene bank environments. Furthermore, although the effectiveness of captive breeding programs are currently under debate and context dependent, sites adjacent to natural ecosystems may be able to provide effective opportunities for captive breeding and wildlife rehabilitation programs.[98, 134]

§ 11.6 Urban habitat type design guidelines

The types of habitats present within an urban core ecosystem have substantial influence on the biodiversity of local ecosystems, as mentioned in Sections 11.5.3 and 11.5.5. Thus, when designing a constructed environment, it is important to determine the types of habitats that will positively influence the biodiversity of local ecosystems within a given context. Furthermore, the types of species that a habitat patch attracts partially depends on the characteristics and qualities of the habitat patch. For example, for early succession species, rock habitat, scrubland, fallowland, sparsely vegetated barrens, and brownfields are important.[231] Thus, the design of individual habitat patches directly influences the potential of the project site to positively contribute to the biodiversity of the local ecosystems. To this end, the following subsections review various habitat types that can be important to consider within the context of urban core ecosystems.

§ 11.6.1 Design for temporal habitat conditions *(successional dynamics_ temporal species behavior + habitat needs)*

The inherent dynamic temporal changes of habitat patches that occur without active maintenance are an important design factor. For instance, the inherent and potential dynamic changes in quality and functions of habitat patches over time are important to consider, in terms of their contribution to the biodiversity of the local ecosystems. For example, from an ecosystem function perspective, mid-succession habitats are particularly important, as they tend to be the most productive habitat types.[223] Furthermore, different species have different habitat needs at different temporal scales, from an hourly scale to seasonal and yearly scales. Concurrently, the qualities and functions of habitats are dynamic: their microclimates, structure, vegetation cover, successional stage, and other habitat functions and qualities change at different time scales.

Within natural ecosystems, individual habitats naturally shift between diverse successional stages, when unimpeded by disturbances.[57] In contrast, constructed ecosystems tend to encounter frequent disturbances, which can promote the development of habitat patches that remain at the early and mid-successional stages. Conversely, late successional stage habitats, such as urban forests, tend to be rare within urban core ecosystems.[9, 57] Moreover, typical existing constructed environments, such as vacant lots and brownfield sites, tend to attract early successional species, which typically are comprised of more non-natives than late successional habitats. It is important to note that the presence of non-natives within a constructed ecosystem can be beneficial in some cases, particularly when establishing habitat patches, as discussed in Section 11.7.1. Similarly, early successional habitats are integral to the promotion of biodiversity within local ecosystems. For instance, a number of endangered butterfly species require early-successional vegetation.[411] Moreover, some of the most abundant, successful early succession species are native, from naturally disturbed habitats such as river banks.[57, 378]

However, typical urban core ecosystems currently tend to have too many early succession habitat patches. Indeed, existing research indicates that the restoration of successional dynamics within urban core ecosystems can improve species richness.[244] In addition, the provision of habitat patches at various succession stages tends to promote indigenous species populations, as well as reduce the quantity of non-native species, which tend to prefer disturbed patches.[314] Thus, typical urban core ecosystems should have more diverse habitat patches, in terms of succession stages, in order to improve their influence on the biodiversity of local ecosystems.

Both ecosystem and individual habitat scale projects can contribute to the restoration of successional dynamics. At the urban core ecosystem scale, the provision of a mosaic of habitats at various successional stages ensures the provision of habitats that are suitable for a diverse range of local species, and has been found to improve species richness, as well as foster local species populations. At the habitat patch scale, allowing habitat patches to transition to different successional stages has been found to increase plant and animal species richness.[244] However, habitat patches must be undisturbed long enough for succession to occur, which is uncommon for typical constructed environments.

Interestingly, habitats that are actively managed to remain at a constant successional stage can also be valuable for biodiversity conservation, depending on the context. However, it is important to note that static succession habitat patches typically require more active management, and therefore more resources, in order to maintain the current succession stage. For instance, in order to provide habitat for certain rare and endangered species, large reserves attempt to maintain a specific successional stage over time. However, actively maintaining large habitat areas at a specific successional stage has oftentimes proven to be quite difficult and costly, due to the scale of these areas, among other limiting factors. As a result, the successional environment areas within these reserves that these species require are decreasing over time, which is eventually resulting in the loss of suitable succession areas and the local loss of rare and endangered species.[231] Small and medium scale habitat patches in adjacent constructed ecosystems have been found to be effective at supplementing these decreasing habitats, thereby sustaining local rare and endangered species populations. This is because it is easier to maintain a small or medium scale habitat patch at a specific successional stage than at the scale of a nature reserve.[231]

Therefore, there are two general types of habitat succession design strategies that can be developed at the building scale: the design of a temporally dynamic or static successional stage habitat patch. The most effective strategy for a building project depends on the adjacency conditions of the building site, as well as the state of the local ecosystems. However, existing literature indicates that generally it is more effective to develop habitat patches at various succession stages and limit patch disturbances, depending on the context.[231, 244] In contrast, in specific cases it can be more appropriate for a building to foster a static habitat patch. For instance, a building site may be able to function as a stepping stone habitat to an adjacent habitat source patch, such as a nature reserve, for endangered species that inhabit late succession stage habitats, if the habitat patch remains in a constant succession stage. Thus, the determination of the type of habitat patch to develop for a specific context, in terms of successional dynamics, is dependent on a diverse array of issues, such as the types of species that have access to the habitat patch, the accessibility of the patch, and the distance to source patches and corridors.

Moreover, it is important for design teams to also take into account the behavior and needs of locally relevant species over various time cycles, such as accounting for species migration and hibernation.

§ 11.6.2 Consider low nutrient and wet habitats

Urbanization typically reduces the quantity and quality of wet and nutrient poor habitats in local ecosystems. Subsequently, less common and rare species that are dependent on these habitats tend to decline.[253, 257] The loss of these types of habitats commonly results in species that prefer nitrogen-rich, warm and dry habitats being overrepresented in cities. These species are often nonnatives.[252] Alternately, the preservation and restoration of low nutrient and wet habitats in urban core ecosystems can increase indigenous common and rare species populations in the local ecosystems, such as fens, bogs, nutrient-poor grasslands, bioswales, and retention ponds. For example, similar to the functions of clusters of garden patches, Gledhill (2008) found the number of ponds, between

2m^2 and 2 ha, within 500 m of a particular pond positively influenced the plant species richness of the pond. Moreover, pond species richness was more significant with pond clusters than a single pond.[172] Thus, small scale ponds can positively contribute to the biodiversity of the local ecosystems, depending on the context.

§ 11.6.3 Design to mimic regional ecosystems

Although there is substantial existing literature that suggests that urban core ecosystems and habitats are novel,[257] there is considerable evidence that suggests that a number of constructed environments are not novel, and that there are natural analogues for a diverse range of constructed environments, as discussed in Section 11.2. To this end, Lundholm (2010) provides a review of a number of examples of habitat types and environmental conditions that are common within urban core ecosystems, and which also have natural analogues within the local region.

For instance, Lundholm (2010) reviewed existing literature on several naturally unproductive and high-stress ecosystems that provide analogues for various constructed ecosystems.[281] For example, there is evidence that plant species within hard surfaced constructed ecosystems tend to be stress tolerant, long term perennials that are native to local natural ecosystems that are predominantly comprised of rocks or shallow soils, such as rock outcrops, cliffs, and shingle beaches.[281] In addition, a number of types of constructed environments that can be found within urban core ecosystems are able to function as analogues for plants and insects that are adapted to floodplains, dunes, and other non-forested habitats.[479] Moreover, constructed environments such as salt mines, factories, and roadsides treated with salt, have fostered species that are typical of salt lakes and marshes, including species native to rare inland salt springs.[378] Moreover, early successional stage natural habitats such as rock habitat, scrubland, fallowland, and sparsely vegetated barrens have been found to be sustained within existing constructed ecosystems.[231] For instance, rubble fields in previously bombed urban areas, as well as roofs covered in crushed concrete and brick, have been found to support rare invertebrates that are attracted to dry, rocky, or sandy natural habitats, such as stony fields.[179] Thus, constructed environments can promote rare species populations for diverse natural habitats within the local region. On the other hand, it is important to note that sometimes it is important to design constructed environments to be less similar to natural analogues, in order to inhibit pest populations and migration.[281]

§ 11.6.4 Design of ecological surfaces, structures + spaces

For native species to colonize artificial substrates and environments, they must be able to arrive at the site, which requires the elimination of dispersal barriers, as discussed in Section 11.4.5, as well as be able to tolerate the conditions of the site. To this end, there are a number of regional species that are capable of colonizing most types of constructed environments and environmental conditions that are common within urban core ecosystems.[281]

It is important for surfaces, structures, and habitats to be designed to be similar to natural structures that are present within the region of the site, if they are intended to promote biodiversity. Otherwise, the design solution may not adequately provide the necessary characteristics to foster native species inhabitation, and thereby prove ineffective. For example, steel and glass walls have been found to deter the growth of typical wall flora. These materials typically do not have natural analogues within the region.[265] Often, relatively slight alterations to the design of hardscapes can greatly improve the potential of constructed environments to foster local species populations. For instance, seemingly insignificant differences in abiotic conditions between natural analogues and constructed environments tend to prevent the colonization of native biota.[281] For example, drilling holes into concrete walls has been found to better support climber vegetation, much like crevices on rock cliffs.[470] Although care needs to be taken to avoid the development of maintenance issues with the wall assembly. In addition, there is evidence that the lack of microhabitat heterogeneity on typical artificial substrates may be the reason these surfaces have a tendency to have less plant diversity than their natural analogues.[263] Thus, it is important for design teams to develop a detailed analysis of potential natural analogues, in order to account for potential seemingly insignificant design factors that can inhibit the ecological performance of the design of a constructed environment.

Furthermore, it is important to note that the various surfaces, spaces, microclimates, and elevations within and around building projects inherently provide an array of opportunities to develop a diverse range of habitats for species with varying habitat requirements. However, as discussed in Section 11.5.7, the development of multiple, diverse habitat patches within a building may not be effective, depending on their connectivity potential, target species, and other contextual factors.

§ 11.6.5 Limit the perceived + actual negative effects of nature on people

The incorporation of natural environments and biota into human communities is not always beneficial for people. For instance, various species, such as snakes and spiders, are perceived as pests, nuisances, and even threats by different cultures throughout the world. In addition, some natural environments pose large scale concerns to the health and well-being of human populations, such as the transmission of West Nile Virus through mosquito bites. Some of these concerns can be addressed through design. For example, placing natural mosquito predators in water containers, as occurs in nature, can eliminate mosquito larvae.[330] In addition, habitats for negatively perceived species can be located in areas of a project that are inaccessible or not visible to building occupants. Furthermore, it is important to note that increased human development in previously undisturbed natural ecosystems can foster exposure to dangerous viruses, such as the outbreak of the Ebola virus in West African countries in 2014 that resulted from the deforestation of pristine ecosystems.[148] Therefore, in some contexts, it is particularly important to avoid human development and disturbances, for the health of human and natural communities.

§ 11.7 Design for species: Exploring the value of designing constructed environments to support various species

Constructed environments can be designed to sustain and support a diverse range of species, depending on the context. The following subsections provide an overview of the potential value of different types of species that have been identified in existing literature as important to sustain. This review is intended to provide design guidelines and general issues to consider when determining the biodiversity potential of various design solutions. However, it is important to note that the relative value of various species and design strategies for a given project, in terms of promoting biodiversity, depends on a variety of contextual design issues, as discussed in Sections 11.4 and 11.5. Moreover, there is substantial evidence that it is important to sustain a diverse range of species, both rare and common, to achieve both biodiversity and ecosystem function goals, as discussed in Sections 11.5.4, 11.5.7, and 11.5.8, as well as Chapter 10. Furthermore, it is important to consider that regardless of a specie's value in terms of the biodiversity and ecosystem function goals for local and global ecosystems, the preservation of 'non-valuable' species can result in higher quality natural and constructed environments, promote ecological behavior, and can help mitigate Shifting Baseline Syndrome, as discussed in Chapter 9.

§ 11.7.1 Design for native versus non-native species

Non-native species are commonly regarded as detrimental to ecosystems, and tend to be cited as a primary cause of the decline of species and the loss of biodiversity within ecosystems.[122, 313] However, existing evidence that suggests that non-native species richness is the primary cause of the decline of native species in disturbed ecosystems tend to be based on simple correlations.[122] Furthermore, there is evidence that habitat loss and transformation associated with urban land use are typically responsible for the decline of previously occurring native species.[257, 281] Often, these human disturbances provide beneficial conditions for non-native species. Indeed, introduced species have been found to prefer disturbed patches, and are able to more quickly and easily colonize disturbed habitats than a number of native species. Thus, non-natives are prevalent in early successional stage habitat patches.[257]

§ 11.7.1.1 Natives

However, there is a growing body of evidence that suggests the primary factors for native species not repopulating urban areas are due to factors other than non-native colonization, such as dispersal barriers, lack of vegetation cover, and human disturbance regimes, as discussed in Section 11.4.4.[179, 281, 470] For instance, some of the most abundant, successful site colonizers are native species.[57] Similarly, the establishment of native plant species has been found to promote an increase in native plants and animals in urban areas.[314] Moreover, when constructed environments are undisturbed long enough for succession to occur, the number of non-natives tends to be reduced.[314] In addition, increased nitrogen availability in urban areas tends to simplify biotic communities and favor exotic species, which suggests that reducing the presence of nitrogen in urban areas could promote the colonization of constructed environments by native species.[195] Furthermore, plant species within a number of Italian cities have been found to be more similar to local natural ecosystems than other cities within the region.[180] Evidence like these examples suggest that the lack of native species within urban areas is due to a number of design issues, which can be changed through the design, development, and maintenance of urban areas. For instance, the provision of gardens has been found to improve native species richness.[68] To this end, habitat disturbances have been found to increase the proportion of annual and biennial species within urban areas, which indicates that species within disturbed sites can be readily replaced through effective design and maintenance strategies.[257]

§ 11.7.1.2 Non-natives

It is important to note that non-native species have the potential to perform beneficial functions in urban areas. For instance, a number of non-natives are non-invasive, and can quickly inhabit early succession constructed environments. In addition, the novel mixtures of non-native and native species that colonize constructed environments after disturbances, have been found to sometimes be better adapted to the conditions of constructed environments than the previous native species communities.[174, 257] Habitat patches with a mix of non-native and native species can potentially strengthen the biodiversity and functions of local ecosystems, by fostering resilient species populations, as well as contributing to the local ecological networks, among other benefits. Thus, non-native, non-invasive species have the potential to aid the repopulation of disturbed habitat patches and contribute to the biodiversity and functions of the local ecosystems. On the other hand, there is evidence that in some cases, non-native species are not effective at providing resources for native species, such as pollinating insects, and that native plants promote higher animal species diversity.[174] Moreover, invasive non-native species have been found to invade adjacent rural and natural ecosystems, as well as displace native species, among other detrimental effects.[287] Therefore, the value of non-native species should be assessed on an individual species basis. However, it is important to note that it is currently difficult to determine if an individual species will be invasive or non-invasive before introducing it to a local ecosystem.[152] Thus, further research into effective methods to determine the influence of introducing various species into a given context is needed.

Forman (1995) proposed a series of design strategies that may limit the introduction of invasive species to a site.[152] For instance, reducing 'empty niches' may be effective, by ensuring that the species necessary to maintain local ecosystem functions are present. Otherwise, invasive species may fill the role gap. Moreover, patches with low species richness have been found to be more susceptible to invasive species. Patch disturbances tend to provide opportunities for invasive and non-invasive non-natives to establish themselves.[281] Furthermore, competition among species reduces the potential of the establishment of invasive species. The alteration of natural disturbances, such as stopping floods in historically flooded areas, can also lead to the establishment of invasive species.

§ 11.7.1.3 Conclusion

Thus, in terms of designing habitat patches to minimize the risk of the establishment of invasive species, the establishment of species from the local ecosystem can be effective. In particular, local species from naturally disturbed habitats, such as river walls, tend to have similar habitat requirements as typical constructed environments.[281] Furthermore, the possible effects of climate change on the potential of native and non-native species to persist within individual constructed environments and overall ecosystems, need to be considered. In some cases, non-native species may be more resilient over the long term.[299, 425] Moreover, due to the vertical nature of buildings, the location of constructed environments within a building will affect the types of species that can inhabit them, and may offer a refuge for native species that require habitats in higher elevations than their current ecosystems provide.

§ 11.7.2 Design for rare + endangered species versus common species

The provision of self-sustaining populations of rare and endangered species has been identified as an important urban biodiversity goal in existing literature.[257] To this end, extant research indicates that urban core ecosystems can foster local rare and native species populations, as discussed in Section 11.4.5. For example, a diverse array of rare species from rare local ecosystems, such as cliffs, bogs, and wetlands, have been found to colonize urban core ecosystems, such as the bumblebee in San Francisco and the common frog in England. This is because they mimic the environmental conditions of natural habitats.[174, 257, 281]

However, although rare and endangered species are important for biodiversity conservation, it is important for design teams to be aware that existing literature indicates that rare and endangered species, in general, aren't effective at providing and sustaining ecosystem services. In contrast, tolerant and common species have been found to support most ecosystem services, due to the resilience of these species to change, as well as their ability to fulfill certain functional criteria.[455] Thus, depending on the context and goals of a building project, design solely for rare and endangered species may not be an effective strategy.

§ 11.7.3 Design for high versus low mobile species

A number of highly mobile species, such as butterflies and birds, have been found to be able to adapt to a diverse range of fragmented ecosystems and habitat patches.[21, 125, 174] However, fragmented ecosystems, particularly urban core ecosystems, tend to have a number of dispersal barriers that limit the ability of less mobile species to inhabit and migrate throughout the constructed environments of these fragmented ecosystems, as discussed in Section 11.4.5. To this end, there are a number of design strategies that can mitigate dispersal barriers and promote the inhabitation and migration of less mobile species. For instance, the provision of continuous habitat patches for less mobile species, such as the development of interconnected ecological corridors and patches, can be effective in some situations, as discussed in Section 11.4.10. Moreover, the provision of resources in close proximity to each other, such as within an individual constructed environment, and to a lesser extent via adjacent compatible habitat patches, can help sustain less mobile species.[410] To this end, it is helpful to understand the general dispersal ranges of various species, in order to develop guidelines for appropriate distances between the various resources these species require. As discussed in Section 11.4.16, the dispersal range of species within urban areas can be greater than within natural ecosystems in some cases.

§ 11.7.4 Exploring the value of existing strategies to support individual species

§ 11.7.4.1 Design for flagship species

A number of researchers have proposed that design for specific types of species can improve the biodiversity of local ecosystems more effectively than design for other species. For instance, the use of flagship species, which typically are large megafauna that are perceived by the public as charismatic, to promote the conservation of an ecosystem or region has been employed in a number of global and local environmental campaigns. However, the conservation of flagship species tends to be expensive, can divert management and conservation priorities away from more threatened species and habitats, and common flagship species tend to be ineffective as umbrella or indicator species.[106, 134, 406] Indeed, there is evidence that smaller species typically function better as umbrella or indicator species.[118] For instance, 95% of animals worldwide are smaller than a chicken egg. These animals tend to have the greatest biomass and effect on ecosystems.[97, 482] Furthermore, if a flagship species becomes extinct, the public's enthusiasm for biodiversity conservation in general may be affected, and their support for the ecosystem the flagship species represented may wane.[406] Thus, it may be more effective to use the resources devoted to the conservation of flagship species to conservation projects that preserve a more diverse range of species, as well as educational programs that focus on the value of a number of less charismatic and smaller species that contribute to the local ecosystems.[193, 406] Moreover, some regions, such as the Alaskan rainforest, do not currently support threatened species, which makes the identification and preservation of flagship species within these regions difficult.[406]

§ 11.7.4.2 Design for keystone species

Keystone species are species that have a disproportionately large effect on the local ecosystem and other species, relative to their abundance or biomass.[364] Thus, preserving these species and the habitats they require, in theory, would be an effective method to preserve local ecosystems and a diverse range of species. However, the results of existing literature indicate that efficient and cost effective methods to identify keystone species may not be possible to develop.[219, 364] Moreover, as discussed in Chapter 10, existing research indicates that a diverse array of species are needed to maintain multiple ecosystem functions, particularly when considering the integrity of ecosystems over time. Furthermore, individual ecosystem functions have been found to be provided by different species during multiple years.[391] In addition, a literature review by Isbell (2011) found that a number of existing studies that were focused on keystone species and ecosystem functions were inaccurate because the research methodologies did not adequately account for the dynamic influences of time, location, functions, and environmental changes.[219] Therefore, existing research suggests that keystone species may not be an effective design strategy, as existing literature indicates that a more diverse range of species are needed to maintain the integrity of ecosystems.

§ 11.7.4.3 Design for umbrella species

Umbrella species are species whose habitat requirements are the same as many other species, and that require large land areas. Theoretically, the protection of the habitat of umbrella species indirectly protects a diverse range of other species that inhabit the same habitats.[99, 103] Umbrella species are sometimes used in conservation strategies to identify the location, minimum size, and composition, structure, and processes that are necessary within a conservation area.[350] However, the effectiveness of umbrella species to protect a diverse range of species has not yet been determined. For instance, Ozaki (2006) found Northern Goshawk owls were not effective as an umbrella species, although it may have been because this species was able to adapt to changes in habitat conditions, such as the use of agriculture and forest habitat patches. Thus, Ozaki (2006) suggests that species that can adapt to habitat conditions may not be suitable umbrella species.[350] Moreover, precise habitat requirements of most species are not yet well understood, and a number of species have very specific habitat requirements that may not be used by umbrella species.[266] Furthermore, existing literature suggests that it is currently very difficult to determine the quantity of umbrella species that are needed for a given ecosystem, as well as the effectiveness of using various species as umbrella species.[406] Thus, existing research suggests that current strategies of identifying and protecting umbrella species are not effective ways to preserve ecosystems and a diverse array of species, and that more comprehensive, multiple method based design strategies are necessary, as discussed in Chapters 8 and 10.

§ 11.7.4.4 Design for indicator species

Indicator species are species that can be used to assess a trait or characteristic of an ecosystem, such as disease outbreak, pollution, or species competition. Some species have been used to indicate biodiversity, while others indicate abiotic conditions or changes in ecological processes. For instance, Lindenmayer (2000) suggests seven types of indicator species. Species whose presence or absence indicates the presence or absence of other species, keystone species, species whose presence demarcates human-generated conditions, such as air and soil pollution, a dominant species that generates a large proportion of the biomass or makes up a large proportion of the individuals in an area, a species that indicates specific environmental conditions, species that function as environmental sensors and warnings of environmental changes, due to their sensitivity to these changes, and management indicator species, which demonstrate the level of influence of a local disturbance or the effectiveness of disturbance mitigation applications.[277] However, it is important to note that it can be difficult to assess the most appropriate species that should function as an indicator species for a given condition or ecosystem. Furthermore, in many cases it is difficult to determine the evaluation criteria for the condition the indicator species is supposed to represent, similar to the discussion on determining effective ecosystem functions for an ecosystem in Chapter 10.[262, 406] Nevertheless, indicator species have been used effectively for bio monitoring to gather information of regions and local and global ecosystems for decades. For instance, mussels and oysters can be used to evaluate the environmental quality of coastal waters, as well as to provide water filtration and potentially a source of income.[277] Thus, indicator species can be used to provide ecosystem functions within urban areas, as well as to monitor various biotic and abiotic conditions of the local ecosystems.

§ 11.7.4.5 Examples of urban indicator species

A number of urban area specific indicator species have been found in existing literature. For instance, amphibians are sensitive to environmental stressors, and thus are used to indicate the quality of urban aquatic environments.[206] Several urban indicator species are briefly discussed in this subsection. A more comprehensive overview of potential urban indicator species is outside of the scope of this chapter.

Breeding birds are highly visible and quite sensitive to changes in habitat structure and composition. They have been used to indicate the success of different park features, such as habitat heterogeneity and habitat structure.[206] For example, bird species richness is generally higher in more vegetated areas.[391] Thus, ecologists consider birds to be good indicators of changes and stresses in urban areas, as well as important to promoting ecological awareness.[391] Savard (2000) provides a more detailed overview of specific bird species and habitat requirements.

There is evidence that butterflies can be effective indicators of the ecological quality of constructed environments. For instance, butterflies have a number of characteristics that make them effective as indicator species. For example, there are a wide range of butterfly species, from common to highly rare, and poor dispersers to high dispersers. This species diversity provides numerous opportunities to assess a number of different environmental conditions. Furthermore, butterflies respond quickly to changes in structure and the botanical composition of habitats. They have short life spans, and have comparatively high habitat specificity.[206] Moreover, butterflies can maintain local populations with relatively small quantities of habitat. Likewise, they are capable of reproducing in large numbers.[410] Most butterfly species avoid dense forests, but require some woody vegetation, which makes them good candidates for urban areas.[231] They are one of a few species groups that can be easily linked with the perception of the quality of nature by humans, which makes them an important indicator of the potential of an environment to promote ecological behavior.[410] Finally, many butterflies are endangered at national and continental levels, which makes design for butterflies within urban areas also important for sustaining the biodiversity of the local region and nation. To this end, butterflies have been found to be indicators of invertebrate diversity in a number of European ecosystems.[411]

§ 11.7.4.6 Conclusion

In conclusion, the effectiveness of the development of design strategies based on the needs of individual species to improve the biodiversity of local ecosystems depends on the context of the project. In addition, there is uncertainty about the roles of many species, as discussed in Chapter 10 and Section 11.2.6.2, due to a number of complex issues such as the altered food webs of urban areas. These issues make it difficult to determine the relative value and influence of individual species to the biodiversity of local ecosystems.

Furthermore, as discussed in Section 11.5.4, existing literature indicates that species diversity is important. Moreover, design for minor species can provide a number of benefits. For example, design for both minor and dominant species that contribute to the same ecosystem function improves the resilience of the ecosystem, and minor species can provide functions during changing conditions.[20] These confounding issues have led researchers to generally suggest a cautious approach to addressing species diversity: the protection of, and design for, diverse species may avert catastrophes.[455] Moreover, similar to the discussion in Section 11.5.4, the results of extant literature indicate that effective design solutions tend to take into account diverse species, habitats, and ecosystem processes, rather than focusing on individual species.

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§ 11.8 Chapter Conclusion

Thus, it is evident that the design of constructed environments and ecosystems substantially influence the biodiversity of local ecosystems. Moreover, design for biodiversity within urban areas can provide diverse benefits to local ecosystems, such as buffer species populations, gene banks, and ecological corridors. In order to develop constructed environments that improve the biodiversity of local ecosystems, it is important for design teams to account for a myriad of contextual design issues and performance parameters. For instance, the effectiveness of various design strategies depends on the context of the design project. For example, within some ecosystems the most effective way to improve the biodiversity of the local ecosystems may be to mitigate urban disturbances, such as water and air pollution, while in other contexts, the design of a habitat patch may be able to foster self-sustaining populations of diverse native species, provide refuge for species whose habitat is vanishing from climate change, or provide essential stepping stone habitat for ecological corridors. Moreover, design teams can develop constructed environments that improve the biodiversity of local ecosystems in numerous ways, through the incorporation of various ecological spatial qualities and biodiversity issues into design solutions. However, it is important for design teams to determine the types of habitats that are most important for constructed environments to sustain within the context of their site, in order for the design solution to effectively contribute to the biodiversity of local ecosystems. In addition, the types of species that inhabit urban areas are partially influenced by the design of constructed environments. As discussed in Section 11.7.4, in most contexts, in terms of promoting species richness, existing literature indicates that design solutions should promote species diversity. However, it is important to consider that it can be important to support and sustain individual species in certain contexts. For instance, constructed environments can function as gene banks for endangered species.

Despite these findings, it is apparent that considerably more research is necessary to comprehensively explore and evaluate the potential of constructed environments within urban areas to improve the biodiversity of local ecosystems, as well as to develop comprehensive design guidelines and biodiversity performance metrics.

Nevertheless, this chapter has identified a number of potentially effective design guidelines, solutions, and biodiversity performance metrics that can aid design teams in developing constructed environments and ecosystems that positively contribute to the biodiversity of the local ecosystems. These results can also be used to explore and evaluate the types of design guidelines that can be developed from existing research, as well as to identify existing research gaps and future research opportunities. Moreover, as discussed in Section 11.3.3, this chapter is intended to function as an initial step towards the development of an effective building scale design for biodiversity support system. The results presented in this chapter demonstrate that such a support system has the potential to provide design teams with diverse opportunities to effectively improve the biodiversity of local ecosystems.

12 Conclusion + Discussion

§ 12.1 Introduction

§ 12.1.1 General conclusion for primary research objective

Taken together, the results of this research project make it evident that the design of constructed environments has a significant impact on the performance and value of building projects, from an economic, social, and ecological perspective. More specifically, the integration of microforests into office environments was found to yield a diverse range of building, worker, and ecological performance benefits.

§ 12.1.2 General research project methodology

In order to effectively investigate the potential of the design of constructed environments to improve the building, worker, and ecological performance of building projects, this research project investigated the performance potential of design from the perspective of diverse research domains, including environmental psychology, ecology, engineering, and design. As discussed in detail in Chapter 1, the Design Research Methodology (DRM) was used to structure this research project. Within this framework, explorative design case studies, literature review, expert interviews, observations, and experimentation research methods were employed, in order to develop design guidelines, high performance space typologies and case studies, as well as assessments of several experiment hypotheses. This diverse research methodology improved the quality of the research project in a variety of ways, including the development of effective feedback loops, more detailed evaluation methods, and the identification and evaluation of otherwise unconsidered research questions, issues, and boundaries, as discussed in Section 12.2.4.5 and Chapter 1.

§ 12.1.3 Chapter contents overview

Detailed conclusions from the various research processes that were conducted are described in Chapters 3-11. In addition, Section 2 summarizes a number of general conclusions that can be drawn from the results of the conducted research studies. These conclusions are discussed based on their impacts on the general performance parameters used in this research project. Furthermore, Section 3 discusses a number of general research limitations that were identified during the course of the research project. Section 4.1 discusses how the results of this research project can be applied in current practice and research endeavors, including effective office building renovation and building system design solutions, while Section 4.2 discusses potential future research directions that the results of this research project indicate have substantial potential to effectively improve the economic, social, and ecological performance of constructed environments, as well as constructed and natural ecosystems.

§ 12.2 Research results overview: Performance benefits of microforests

§ 12.2.1 Building performance

Based on the results of the research discussed in Chapters 3, 4, and 5, it is evident that the design of buildings can be integrated into the design of building systems in ways that improve their performance. In other words, the development of building infrastructure systems that integrate technical solutions with the design of spaces, which can be defined as spatial infrastructure, can be more effective than design solutions that solely incorporate high performance technical solutions. For instance, current 'high performance' technical systems have been found to operate at 20-50% less efficiency than their estimated performance potential. One of the reasons for this discrepancy between predicted and actual performance is the inability of technical systems to adequately address occupant behavior, among other issues, such as a typical dearth of building system optimization and maintenance conducted in existing buildings.[64, 260, 468]

Through the course of this research project, microforests have been found to be a particularly effective design solution, in terms of improving building performance through the integration of technical solutions with the design of spaces. As described in Chapter 1, the effects of microforests on the performance of office buildings was studied through three performance perspectives:

- *How can microforests reduce operating costs?*
- *How can microforests improve the performance of building systems?*
- *How can microforests reduce construction costs?*

In terms of construction and maintenance costs, microforests can be more cost effective than a number of existing office planting strategies, as discussed in Chapter 3. Moreover, in terms of energy use, vegetation shading strategies were found to be as effective as typical shading solutions, as discussed in Chapter 4. In addition, the occupation of a semi-outdoor high quality microforest courtyard was found to reduce the energy consumption rate of an office building in Accra, Ghana more than physically shading the building. Similarly, the presence of dense vegetation in an office work environment was found to increase the thermal comfort range of occupants. This increase in thermal comfort promotes the temperature set point to be raised in summer and lowered in the winter, and thereby leads to reductions in the energy consumption rate of buildings, as described in Chapter 5. These findings suggest that, in terms of building energy consumption, the design of space for occupant well-being and performance can be more effective than designing a space to directly minimize energy use, such as through shading strategies. Moreover, taken together, these findings suggest that the psychological benefits of plants are greater than the physiological benefits of plants. Thus, the potential psychological benefits of incorporating microforests into office buildings was investigated in this research project, as discussed in Section 2.2.

§ 12.2.2 Worker performance

This research project investigated the potential of office environments to influence worker performance and well-being. Specifically, as discussed in Chapter 1, the effects of microforests, as well as typical workspace types, on worker performance were evaluated through two performance perspectives:

- *What types of constructed + natural workspace types, and spatial qualities, improve worker performance?*
- *Does the occupation of microforests influence occupant thermal comfort?*

Generally, the results of this research project, as well as existing literature, suggest that the design of work environments substantially impacts worker performance. To this end, the results of Chapters 6 and 7 indicate that workers benefit from more diverse work environments than are currently provided. For instance, the two studies discussed in Chapter 7 evaluated the types of typical and natural workspaces and spatial qualities that knowledge workers prefer, in regards to conducting various work tasks. The results of these studies indicate that microforests can be more effective than existing workspace types for a diverse range of work tasks.

Furthermore, it is important to note that different types of microforests, typical workspace types, and spatial qualities were found to be preferred and beneficial for different types of work tasks, as discussed in Chapter 7. Thus, the results of these studies suggest that the provision of innovative workspace types and spatial qualities in existing and future work environments can positively impact the work performance of the occupants. Moreover, the results of the thermal comfort study discussed in Chapter 5 indicates that microforests can improve occupant thermal comfort as well. Similarly, the results of these studies indicate that existing office environment work types and spatial qualities are not maximizing worker performance and well-being, and should be reconsidered in order to improve the economic performance of companies and the well-being of building occupants. To this end, Section 4.1 discusses the application potential of these findings, and Section 4.2 describes several future office design research topics that may yield substantial benefits.

§ 12.2.3 Ecological performance

§ 12.2.3.1 Identifying the importance of substantially improving the integrity of local + global natural ecosystems

It is clear that the current state and quantity of local and global ecosystems, as discussed in Chapters 8-11, is at precarious and unsustainable levels, with a substantive number of local and global ecosystems projected to be destroyed or collapse within the next fifty years, and the quantity of biota and species diversity rapidly diminishing.[326, 454, 482, 483] Moreover, it is evident that community development and consumption based lifestyles are the primary cause of the ecological degradation, and in many cases extinguishment, of natural ecosystems and biota.[9, 130, 150, 455, 463]

Thus, the current negative state of natural ecosystems and processes, and their effects on human communities, demonstrate that if human communities do not rapidly develop and put into practice alternate ecological community development and lifestyle solutions, local and global natural ecosystems will collapse at systemic levels. In turn, this systemic ecological collapse will forcibly transition human communities and lifestyles into substantially unstable economic and social conditions, drastically reduce the quality of life of individuals and communities throughout the globe, and in many cases, foster recurring and pervasive life threatening conditions.[94, 445] Indeed, these drastic effects of overexploiting natural ecosystems are already occurring, albeit not yet at the sustained global scale that is projected to occur in the coming decades, as evidenced through the effects of natural disasters, droughts, and heat waves, among other current deleterious effects of climate change and natural ecosystem degradation.

Unfortunately, the importance of sustaining the ecological integrity of natural ecosystems is currently discussed and addressed in politics and research much less than carbon emissions. However, it is clear that solely mitigating carbon emissions to manageable levels will not sufficiently address the poor state and systemic collapse of natural ecosystems throughout the globe, nor the resultant substantive deleterious effects on human communities and lifestyles, which are increasingly happening now and in the near future.[130, 296, 384, 482]

§ 12.2.3.2 Exploring the potential of architecture to help improve the integrity of local + global natural ecosystems

It is important to note that the results of this research project, among other existing studies, indicate that the design of constructed environments can substantively influence the impacts of constructed ecosystems on natural ecosystems in diverse ways. Nevertheless, there is relatively scant existing research on the potential, and relative effectiveness, of constructed environments and ecosystems to improve the ecological integrity of local and global ecosystems. To this end, this research project explored the potential of the design of constructed environments to influence the ecological integrity of local natural and constructed ecosystems, based on the results of existing research, expert interviews, and design case studies. As discussed in Chapter 1, the potential effects of microforests on the ecological performance of building projects and local ecosystems were explored through three performance perspectives:

- *What is the potential of buildings to improve the ecological functions of local ecosystems?*
- *What is the potential of buildings to improve the ecological behavior of occupants?*
- *What is the potential of buildings to improve the biodiversity of local ecosystems?*

Moreover, design strategies to improve the ecological integrity of natural ecosystems can be organized into three general performance based design categories: design for ecological behavior, ecosystem functions, and biodiversity. It is important to note that the results of this research project indicate that design strategies that are focused on addressing one of these categories can sometimes inherently address issues in the other categories simultaneously.

For example, design strategies that promote positive, stimulating experiences in natural environments can promote diverse ecological behaviors, including the reduction of the resource consumption of occupants, as well as reducing urban sprawl, through the improvement of the quality of urban core ecosystems, as well as by increasing individual's and community's valuation of preserving and restoring natural ecosystems, as discussed in Chapter 9. In addition, the provision of sustainable local habitat populations of mobile species can improve the biodiversity of local natural ecosystems, as well as promote ecological behavior, by increasing the quantity and quality of daily interactions local communities have with natural stimuli.

However, as discussed in Chapter 11, depending on the context of the project, directly addressing biodiversity at the scale of mid-size office buildings is oftentimes not as effective as design solutions that promote ecological behavior and ecosystem functions, due to scalar limitations. For instance, the relatively small scale of habitat patches that can be integrated within and on office buildings tends to inhibit the ability of the patch to function as a source habitat patch. In comparison, the provision of a dense residential building within an urban core ecosystem, in lieu of providing detached single family homes for the same individuals in rural developments, can potentially preserve and restore much greater proportions of natural ecosystems. Moreover, addressing rural developments is an essential ecological issue, as rural developments occupied almost 25% of the terrestrial land in the US in 2000, which is nearly 15 times the area of higher density urban developments, as discussed in Chapter 8. Thus, within urban core ecosystem sites, design strategies that promote ecological behavior, such as by providing high density residential units that potential and existing residents would prefer to live in, as well as design strategies that improve the functions of urban core ecosystems, are often more effective for promoting biodiversity within local ecosystems than providing habitats, such as microforests, and other direct biodiversity design strategies, depending on the context. Nevertheless, it is important to consider that buildings can contribute to the biodiversity of local ecosystems in numerous ways, oftentimes in concert with design for ecological behavior and function strategies. For instance, microforests can function as gene banks for local rare and endangered species, contribute to local ecological corridors, as well as function as part of a cluster of small scale habitat patches for local rare and endangered species.

Furthermore, the integration of microforests into buildings provides opportunities to incorporate a diverse range of human activities into natural environments, such as workspace for various work tasks. In turn, these types of design strategies can promote the preservation and restoration of natural ecosystems by providing opportunities for occupants to have positive experiences with local natural environments, while also improving the well-being and performance of occupants, as discussed in Chapters 7 and 9. In fact, the development of design solutions that address building, worker, and ecological performance parameters can be mutually beneficial to the primary performance goals of building projects, in regards to all three performance categories, as discussed in Section 2.4.

§ 12.2.4 Integrated performance

§ 12.2.4.1 Identifying general benefits of developing multivalent microforest design solutions

This research project also investigated the potential of constructed environments, particularly microforests, to be designed in a way that effectively addresses multiple performance goals simultaneously. This investigation was conducted through evaluating the following research question:

- *What are the symbiotic interrelationships between the diverse performance parameters explored in this research project?*

The potential economic, social, and ecological benefits of microforests, as well as their potential interrelationships, are illustrated in Figure 12.1. It is important to note the inherent interrelatedness of the various potential performance parameters. For instance, designing work environments to improve worker performance can simultaneously improve the ecological and building performance of the project, depending on the design solution, as discussed in more detail in Sections 12.2.4.2 - 12.2.4.5. Furthermore, the results of this research project demonstrate, through diverse research methods and studies, that the design and development of higher quality spatial environments can improve the economic, social, and ecological performance of constructed environments, as well as local communities and natural ecosystems. Moreover, not only can high quality design solutions improve the performance of building projects and their local context in diverse ways, but they can promote the generation of higher quality lifestyles and spatial environments than existing constructed environments and research indicate are possible. This finding is discussed in more detail in Section 12.2.4.5.

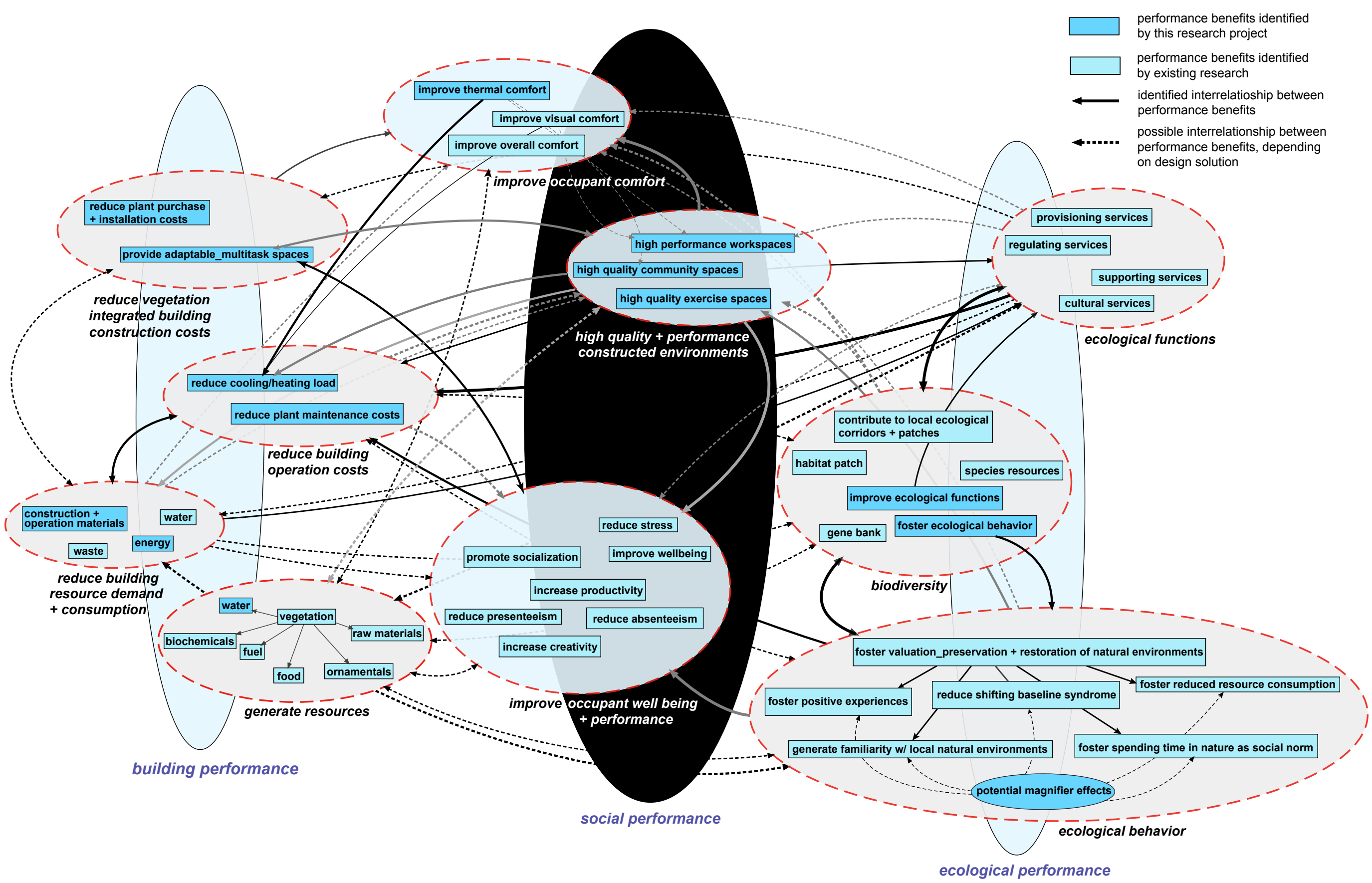

FIGURE 12.1 Potential economic, social, and ecological benefits of microforests, and their potential interrelationships

§ 12.2.4.2 Mulitvalent space types: worker + building benefits

In the surveys described in Chapter 7, various types of microforests can improve the work performance of occupants better than existing workspace types, in regards to a number of work tasks. Moreover, since microforests can provide effective workspaces for multiple tasks, the integration of microforests into office environments can reduce the overall space requirements for a company. Thus, these types of high quality design solutions will substantially reduce the operating and construction costs of the building, as described in Chapter 3.

§ 12.2.4.3 Economic benefits: building versus worker performance

From a financial perspective, design solutions that improve work performance are substantially more effective than design solutions that reduce the energy costs of buildings, as discussed in Chapter 4. In other words, the design and development of high quality environments that improve worker performance are more profitable for companies than reducing the energy costs of their buildings. Moreover, high quality design solutions, such as microforests, can improve worker performance, as well as reduce building energy costs, as discussed in Chapters 4,5, and 7.

§ 12.2.4.4 Benefits of integrating the design of technical systems with the design of building spaces

Furthermore, from a building systems perspective, the presented findings demonstrate that the design and development of building infrastructure systems that integrate high performance technical system design with the design of building spaces can be more effective and higher performing, both in terms of the performance of building systems and workers, as well as in terms of providing otherwise unattainable benefits. For instance, depending on the design solution, the development of positively stimulating experiences with natural environments and resources through the design of high quality spaces can also promote ecological behavior, as discussed in Chapter 9 and illustrated in Figure 12.1.

§ 12.2.4.5 Outcomes of utilizing Design Research Methodology (DRM)

Identifying the value of incorporating DRM into the design research process

The utilization of the Design Research Methodology to structure the research project provided diverse opportunities to improve the rigor, value, scope, and results of the research project. For example, the DRM methodology facilitated the integration of design into the research process in an effective and efficient manner. Specifically, design case studies and processes informed and contributed to the various data collection and analysis methods and studies, as well as conclusions, developed within this research project. For instance, by organizing the research project within the DRM framework, the author was able to identify how various design processes could be implemented in ways that generated feedback loops that informed the development and focus of the experiments and observations. For example, the design of the courtyard in the NLC case study project discussed in Chapter 4 was developed as an initial step towards exploring and identifying potential, previously unidentified building and worker performance benefits that can be attained through the occupation of spatial vegetated environments. At the same time, the development of this design case study provided the opportunity to apply the results of the initial systematic literature review and expert interviews, which were developed in the RC phase of this research project, to a real world building project. This research process generated real world feedback loops. In addition, the application of these findings allowed for further evaluation of the validity and application potential of existing findings. For instance, through the development of energy models for several potential design solutions, as well as through a number of other research methods which are described in detail in Chapter 4, it was determined that the occupation of the courtyard could have a larger impact on the building's energy consumption rate than shading the courtyard. This finding, in turn, resulted in the identification and application of a number of potential psychological performance benefits that can be attained through the design of spaces, particularly microforests, as discussed in Chapter 4. The value of these potential psychological performance benefits indicated that the potential psychological benefits of inhabiting and interacting with microforests merited further investigation. In order to further investigate these potential performance benefits, the study presented in Chapter 7 was designed and developed. Hence, the development of the design case study in Chapter 4 led directly to the identification and development of additional research studies that were not included in the original research project plan, as well as resulted in the identification of the relative value of the psychological performance benefits of vegetation at the scale of an individual building space, compared to their potential physiological performance benefits, as discussed in Chapter 4. As another example of the contribution of design processes and case studies to the development of the research project, as well as the value of integrating design processes and case studies into the developed DRM methodology, the energy modeling process of the various vegetation design solutions that was developed for the case study in Chapter 4 resulted in the identification of the inability of currently available commercial energy modeling programs to account for the shading effects of various types of vegetation and shade devices. This existing research gap is discussed in more detail in Chapter 4. Therefore, the incorporation of design processes and projects into this research project improved the quality, quantity, scope, and depth of the scientific studies and validation methods that were utilized and developed in this research project. Moreover, the DRM structure facilitated the validation of existing research findings and findings that were developed in this research project, from the perspective of multiple performance parameters and research domains. For instance, by developing building design case study projects after the experiments and observation studies for this research project were conducted, it was possible to generate additional validation of the results of the experiments, observations, literature reviews, and expert input, as well as evaluate their application potential. For instance, the building design case study projects that were developed after the experiments and observations were conducted allowed for further validation of the results of the experiments, observations, literature reviews, and expert input, as well as the evaluation of their application potential. For instance, the application of the findings from the studies conducted in Chapters 4, 5, 6, and 7 to the Urban Mountain and LGT design case studies provided feedback loops on the application potential of the findings from these studies to real world projects, via feedback from design teams, engineers, developers, as well as through the development of design processes that investigated the application potential of the various findings of this research project into the specific contexts and constraints of the building projects that were incorporated into this research project. Specifically, the developer associated with the Urban Mountain project was less interested in the aesthetic benefits of vegetation, and was found to be more willing to invest in incorporating microforests, and vegetation in general, into their office building if clear, financially profitable performance benefits could be demonstrated through existing research, and achieved through design. Thus, this project allowed for the application of the research findings that were identified and developed in this research project to a building project that was focused on the potential economic performance benefits of microforests. To this end, the developer found the potential benefits of microforests to be a better solution than more typical planting strategies that were initially proposed, such as green walls.

This feedback supported the value of the studies conducted in this research project to the construction industry, and also identified the importance of developing performance based design projects. Moreover, from a design point of view, this feedback illustrated the value of incorporating performance based design perspectives and solutions into the design process. These findings were also identified in discussions and collaborations with the design team of the LGT project, thereby providing additional validation of these findings. Since the LGT project was a mixed-use development project, this design case study provided the opportunity to evaluate the application potential of the research findings to different building programs, namely residential and creative start up work live unit common spaces. Moreover, since the developer of this project was more interested in worker performance benefits, albeit from an economic perspective, and the design team was particularly interested in the potential ecological performance benefits of microforests that could be developed in ways that improved the economic performance of the project, this case study allowed for the evaluation of the application potential of the results of the developed studies from slightly different perspectives, as discussed in Chapter 1. Hence, the DRM structure provided methods to use design processes both as exploratory research tools, as well as research validation methods.

Thus, the DRM framework allowed for the organization and development of diverse research methods in ways that generated symbiotic interrelationships between the various research processes, in ways that improved the rigor, scope, and depth of the research project, as well as facilitated the identification and development of deeper research questions and studies than were originally developed. Therefore, the use of diverse research methods, and the planned timing of their implementation in a manner that allowed for them to provide feedback loops to the other research methods, benefited the research project in diverse ways.

Identifying the value of incorporating DRM into the design process of constructed environments

The incorporation of experimentation and observation research methods into the research project improved the author's building and space design process in diverse ways, such as by fostering the development of certain skillsets, design research methods, and critical thinking strategies and perspectives that are not usually engaged through typical architecture practice. For instance, the author participated in diverse, detailed discussions with 64 knowledge workers about their perceptions and preferences of different types of typical workspaces and natural spatial environments, as well as spatial qualities, through the development of the space type and quality preference study discussed in Chapter 7. Similarly, the results of this study provided unique insights into the perceived preference for, and value of, various space types and spatial qualities by knowledge workers for various work tasks. These experiences provided more in-depth investigations into the environmental perceptions and preferences of occupants, as well as more diverse design and performance perspectives, than architects are typically exposed to in school and in practice, as well as identified workspace design issues that have yet to be identified in existing research, as discussed in Chapter 7. Moreover, it is clear from the results of this study, as well as related studies, that these types of research processes can positively inform design processes and solutions, and can be an effective 'design tool' within the 'design toolkit' of design teams.

In addition, the incorporation of the diverse and dynamic DRM research methodology and structure into the design process of buildings and spatial environments requires the design researcher to conceive of design in multi-stage phases that evaluate the existing situation (RC + DS-I phases), explore alternative solutions to existing situations (RC + PS phases), and evaluate the results of the various design research processes that were developed (DS-II phase). This design approach is markedly different from typical design processes, such as the requirement to explore and identify existing findings on the performance potential of various design solutions and strategies, develop research studies to explore and evaluate innovative potential design solutions and strategies, as well as the requirement to validate the performance of design solutions.

This rigorous design research approach can generate a myriad of benefits. For instance, by systematically structuring the components of the research project into discrete, clear phases with individual phase objectives, such as the RC, DS-I, PS, and DS-II phase objectives and research methods described in Chapter 1, the author was challenged to strategically plan, develop, and interlink the various research and design processes and studies in systematic ways that maximized the potential benefits of individual studies to each other and the overall goals of the research project, generated effective feedback loops, and explored research questions through diverse design research methods and perspectives. The application and development of this dynamic, systematically structured research process generated additional opportunities to validate the various research studies, from diverse performance and design perspectives, as well as fostered opportunities for developing innovative findings, such as the results that were developed by combining energy modeling, design, and literature review research methods in the design case study presented in Chapter 4.

This structured design research process provided unique opportunities to identify and evaluate the potential benefits and feedback loops of the individual research processes and studies developed in this research project, as well as the performance potential of various types of design solutions. Moreover, the development of this design research process taught the author how to interlink seemingly disparate design and performance goals, such as reducing energy use, improving worker performance, and improving the aesthetic quality of the design solution. For example, in the case of the design research case study presented in Chapter 4, the investigation of the effects of designing a high quality vegetated courtyard space on both worker performance and building energy consumption rates revealed that design for worker performance, in ways that improve the aesthetic quality and social performance of the design solution, can simultaneously improve building energy consumption rates, depending on the design solution, as discussed in Chapter 4. Moreover, the development of systematic literature reviews, and the application of the results of these studies to the design of buildings, building spaces, and spatial qualities from multiple performance perspectives, such as in the project discussed in Chapter 4, as well as the Frankenheerd design for biodiversity office building design case study discussed in Chapter 1, proved to be effective methods to apply research to building projects in ways that improve their performance and design potential. However, it is important to note that, in general, the range of identified potential building, social, and ecological performance benefits that the design of constructed environments can generate is relatively scant, and requires further research in order to effectively inform the design of constructed environments, as discussed in the building, worker, and ecological performance chapters. To this end, the development of systematic literature reviews, as well as observation studies and experiments, paired with design case studies promotes the identification of existing research gaps, such as the energy modeling issue that was identified in Chapter 4 and discussed previously in this subsection. In addition, this paired design research method promotes the development of literature reviews, observation studies, and experiments, in ways that inform design projects from a performance perspective.

Thus, the diverse research methods and processes employed in this research project promoted the exploration and evaluation of design projects from more diverse design and performance perspectives, as well as improved the economic, social, and ecological performance, as well as aesthetic quality, of the design solutions that were developed as part of this research project. Furthermore, it is apparent that symbiotic interrelationships can be developed between research and design, wherein design can inform subsequent research studies and processes, and in turn, research studies and processes can inform and improve design solutions.

§ 12.2.4.6 Conclusion

Therefore, the results of this research project demonstrate that integrating natural environments, such as microforests, into office environments can provide a myriad of benefits effectively and efficiently, in regards to a diverse range of performance parameters. Moreover, the development of constructed environments from a performance based perspective can provide a myriad of benefits simultaneously, in terms of a variety of performance parameters.

§ 12.3 Research limitations

As discussed throughout Section 2 and the various chapters of this book, the scope of this research project was limited by a number of factors. Several specific limitations of this research project that directly relate to the discussions within this chapter are reviewed in the following subsections. Detailed discussions of specific limitations of the various research methods conducted in this research project are discussed in their respective chapters.

§ 12.3.1 Omissions

Although the author worked with several design teams and developers on integrating microforests into real world projects throughout the course of this research project, a microforest was not built through any of these collaborations. The development of a microforest into a project, including the documentation of the design and construction process, would provide unique results, both in terms of evaluating the benefits of microforests, and in terms of determining how to effectively integrate high quality building spaces into building projects. Nevertheless, the results presented in this research project provide ample evidence that justify the development of microforests, in terms of costs and benefits to building owners, occupants, and local human and natural communities.

Moreover, as discussed throughout this book, the development of a comprehensive design support system, from an economic, worker, and ecological performance perspective, was found to be outside the scope of this research project. Substantially more research is needed within these general performance parameters to be able to develop an effective and comprehensive performance based design support system. Regardless, the results of this research project identify important existing research gaps, as well as identify, and in some cases evaluate, potentially important performance parameters and design opportunities, which can aid in the development of a comprehensive design support system. Moreover, it is important to consider that due to the dynamic and complex nature of constructed environments and ecosystems, it may not be possible to develop a comprehensive design support system that effectively identifies and evaluates the relative value of every performance parameter of a given project. To this end, design guidelines and high performance examples are particularly important, as they may be the best methods to aid design teams in developing high performance and high quality constructed environments, in lieu of a comprehensive design support system.

§ 12.3.2 Uncertainties

As discussed in Chapter 7, the evaluation of the performance of knowledge workers in various space types for various work tasks via an image based, semi-structured questionnaire does not allow for the results to be generalized and used as design guidelines for office environments throughout the world, in various cultures and geographical locations. Further research should explore the influence of diverse cultures and physical contexts, such as communities within tropical, desert, or temperate forest regions, on the performance of workers within various space types. Moreover, future research should investigate the real world performance of workers in various space types.

In terms of ecological performance, the discussions within Chapters 8-11 suggest that determining the most effective design strategies, in terms of improving the ecological integrity of local ecosystems, is inherently context dependent and requires further research. Moreover, effective constructed environment and ecosystem evaluation methods are necessary to determine the performance of various design solutions. However, as discussed in Section 3.1, a comprehensive ecological design support system has not yet been developed. Nevertheless, the discussions within Chapters 8-11 can aid design teams through the identification of design guidelines, by providing design teams with a greater understanding of the relative value of various design solutions and ecological performance parameters, and through identifying rough evaluation methods and potentially effective design solutions.

§ 12.3.3 Research limitations conclusions

This research project was limited in a number of ways, as discussed throughout this section and the individual chapters of this book. Regardless, the diverse research methods that were employed in this research project provided diverse design and evaluation perspectives that improved the robustness and depth of this research project. Therefore, although the relative lack of existing research in a number of the topics that were investigated in this research project generated a variety of research limitations, the explorative and diverse research methodology that were incorporated into this research project resulted in the development of a myriad of results that exceeded the original expectations of the author, in regards to the expected research output of this research project.

§ 12.4 Recommendations

§ 12.4.1 Design research application potential

This research project resulted in the development of a number of high performance design case studies, microforest space types, design strategies and guidelines, and evaluated hypotheses, in regards to building, worker, and ecological performance. These results can be utilized by design teams when developing both new construction and renovation projects, in terms of developing and evaluating the effectiveness of various design solutions.

For instance, the results of this research project can aid in the development of comprehensive design support systems and building project performance metric systems, as well as identify, and in some cases evaluate, potentially high performing, innovative design solutions and strategies. For example, the results of Chapters 6 and 7 can aid design teams in determining the types of workspaces and spatial qualities that office building environments should include to maximize worker performance. However, in this case, it is important to note that further research is necessary to effectively determine the relative influence of various workspace types on worker performance. Nevertheless, the presented findings can be used as initial design guidelines.

For example, although existing research indicates that views of plants can be beneficial to the well-being and performance of building occupants, depending on the context, office buildings may not provide views of natural environments. Moreover, within office environments that provide views of natural environments along the perimeter of the building, workspaces within the core of these work environments oftentimes do not have visual access to these perimeter views.[204, 451] An interior microforest can function as a solution to this design challenge, by providing a view to a natural environment from interior office workspaces, and also providing workspaces within the microforest, as in the case of the courtyard in the NLC office building project discussed in Chapter 4.

To this end, it is important to note that the relative value of microforests for a specific building project is dependent on the context. For instance, in terms of the performance and well-being of workers, microforests, and natural environments in general, may be more important in areas of sensuous and natural poverty: areas that do not have adequate quantities of accessible natural and sensuous environments to sustain the local community. For example, the occupants of the Lumen research office building in Alterra, Wageningen rarely use the interior microforests in the summertime. The building occupants report that this is because there is a pleasant forest area nearby, which they prefer to walk through. However, in the wintertime, when this adjacent deciduous forest is bare, and the outdoor temperatures are uncomfortably low, the interior microforest becomes more frequently used. Although further research is necessary to determine the precise reasons for the preferred use of the natural forest environment, the occupants indicated that their preference was due to the larger area of the forest, which allows for leisurely and strenuous individual and group exercise. In addition, the forest was perceived as a more natural environment than the microforests. Thus, the results of this research project indicate that the accessibility of natural environments from a building project impacts the social performance potential of microforests. Moreover, the perceived cohesiveness of microforest design solutions impacts the social performance potential of microforests, as discussed in Chapter 2.

However, it is also important to consider that the occupants of the Lumen building also noted a lack of furniture in the provided microforests, which limits the usability of the spaces. In addition, the occupants noted that they perceived the microforests more as gardens than forest environments, which was also noted as the design intention by the design architect. These factors may also be important contributing factors to the findings, as more cohesive, accessible, and usable microforests may result in greater use of the interior nature spaces. Moreover, internal microforests provide an opportunity to inhabit a sensuous, natural environment in every season, and throughout all weather conditions; microforests are Omni-seasonal. Whether it is raining, humid, snowing, or cold outside, microforests can provide a cohesive, comfortable, and occupiable natural environment.

Hence, it is important to note that the results of this research project do not demonstrate that microforests can, or should, replace the experience of natural environments. Similarly, the provision of microforests does not promote the continued separation between indoors and outdoors. On the contrary, the results of this research project indicate that by incorporating nature into interior environments, people become more motivated to occupy natural environments, as well as value natural environments more, as discussed in Chapter 9.

Furthermore, a number of the presented findings can also be insightful for a range of other disciplines. For instance, the finding that building infrastructure systems that incorporate both high performance technical solutions and high quality space designs can be more effective, can be used by mechanical engineers and architects to develop innovative, higher performing building systems that integrate infrastructure systems into the spatial design of buildings in ways that improve the performance of buildings, the building occupants, and local ecosystems, as well as the quality of buildings and building spaces. Moreover, this finding highlights the need for more quality based performance parameters to be integrated into typical building performance metric systems, such as building energy modeling and analysis programs.

Thus, the interdisciplinary nature of this research project resulted in the development of research findings that can be useful for a number of disciplines, and suggests that there is substantial potential, and need, for future work in related disciplines to be more interdisciplinary in nature. For instance, collaborations between architects and energy model developers can result in the development of energy analysis tools that effectively account for the effects of various design solutions on the performance of mechanical systems, such as the effects of passive design strategies and vegetation. Similarly, the findings in Chapter 7 indicate that there is substantial potential for innovative workspace types to improve worker performance. However, as discussed in Chapter 6, the influence of physical work environments on worker performance has received relatively scant research attention. Therefore, collaborations between environmental and occupational psychologists, as well as architects, could provide opportunities to effectively identify and evaluate the potential of physical work environments to improve worker performance, and may result in the development of substantially more effective work environments.

§ 12.4.2 Future research directions

Throughout the course of this research project, it became apparent that the incorporation of high quality spaces, such as microforests, into building projects were perceived as additional, unnecessary expenses to developers. However, in a number of cases, it was interesting to note that developers were interested in design solutions that provided clear performance benefits. In other words, in some cases, developers were willing to invest in high quality design solutions, if these solutions effectively provided clear performance benefits. For instance, the developer, and jury, of the Oslo office building renovation competition project that was developed in collaboration with a design team that included Schmidt Hammer Lassen and Transsolar, specifically requested vegetation design solutions that provided economic and social performance benefits. To this end, the results of this research project indicate that natural environments can be particularly effective, when designed using a rigorous, performance based methodology. Furthermore, these results suggest that it is important for future research to explore the performance potential of other potentially high quality, sensuously engaging spatial environments.

Through working on these types of design projects, it became clear that the benefits of integrating high quality design solutions into building projects, particularly microforests, are most effective when they are treated as a shared resource, between the local municipality, the building owner, and the building occupants. In other words, the most effective and efficient design solutions are integrated design solutions: design strategies that integrate municipal infrastructure systems into buildings and landscapes. These types of design solutions can be defined as hybrid infrastructure.

The development of hybrid infrastructure can provide a diverse range of benefits to local municipalities, building owners, occupants, and local and global natural ecosystems. For instance, hybrid infrastructure involves the sharing of the costs of building construction and operation between the local municipality and building owner. It is important to note that these financial systems already exist throughout the world, such as municipal green roof, bio swale, and solar panel subsidies and feed-in tariffs,[92, 120, 303, 328] as well as municipal storm water fee discounts for property owners that reduce the impervious area of their site and provide onsite storm water retention.[444] By sharing the costs of integrating municipal infrastructure into buildings, hybrid infrastructure solutions become more cost effective for building owners and municipalities. Moreover, by exploring the potential of innovative hybrid infrastructure systems and design solutions, more effective and efficient solutions may be developed. The results of these types of explorations can result in further reducing construction and operation costs of buildings and municipal infrastructure systems.

Furthermore, hybrid infrastructure can reduce the costs of the infrastructure systems of the local municipality in a variety of contexts, as well as improve the resilience of municipal infrastructure systems. For instance, decentralized wastewater infrastructure systems can be more cost effective than centralized wastewater infrastructure systems in some cases.[170, 446, 469]

In addition, hybrid infrastructure can provide additional high performance rentable space to building owners, as in the case of the constructed wetland in the NLC project in Chapter 4. In this project, a constructed wetland was developed within a semi-outdoor courtyard, and was designed to provide storm water retention and filtration functions. This space could also be designed to provide high quality workspaces that improve the performance of workers in a range of work tasks, as discussed in Chapter 7. Thus, the building owner would be able to rent the workspaces within the wetland at a higher rate than typical workspaces, as they would be high performance workspaces. Therefore, these types of spatial infrastructure design solutions can reduce the costs of infrastructure systems by incorporating rentable space into the infrastructure systems

The development of hybrid infrastructure also provides the opportunity to provide high quality community spaces. For instance, the constructed wetland courtyard in the NLC project discussed in Chapter 4 can potentially be used as a public park and meeting space for members of the local community after business hours.

From an ecological perspective, the coordinated development of a network of hybrid infrastructure integrated constructed environments that are designed to improve the functions and ecological integrity of local ecosystems, throughout an urban area, can mitigate the myriad of negative effects that urban areas have on local ecosystems and communities. These types of ecological constructed environment networks can foster the development of ecologically positive communities, whose development and operations improve the ecological integrity of local natural ecosystems, in comparison to the state of the ecological integrity of local natural ecosystems prior to the development of the urban area.

Thus, the integration of municipal infrastructure systems and space designs can improve the quality and performance of buildings, cities, and municipal infrastructure systems, and inherently provides opportunities for design teams to develop high quality spaces, while also providing diverse performance benefits. For instance, by incorporating the design of building spaces into municipal and building infrastructure systems, the cost of incorporating high quality spaces into building projects can be reduced substantially.

§ 12.5 Final research statement

It is important to note that this research project has only scratched the surface of determining the potential of design to improve the building, occupant, and ecological performance of building projects. Nevertheless, emerging research from numerous research domains indicates that the design of buildings can provide a diverse range of performance benefits, from the potential value of innovative and interactive building materials,[44, 272] to the potential of design to alleviate poverty,[18] to the potential benefits of designing high quality buildings and building spaces.[292, 293, 296]

The results of this research project, as well as findings from existing literature, indicate that design can help solve our society's most dire problems, such as climate change and ecosystem destruction, while at the same time, improve the quality of our local and global communities, if we continue to ask deeper design questions:

- *How can the design of buildings improve the health of its occupants?*
- *How can the design of buildings improve the ecological integrity of the local ecosystems?*

- *How can architecture help make the world a better place?*

Appendix A

Summary Descriptive Statistics for C1 W + C1 E

Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	1938	21.29	24.51	22.69	0.75
Relative Humidity (%)	1938	18.19	71.10	37.63	13.92
Lux *(lm/m²)*	1938	74.90	1383.60	350.59	192.49
Metabolic rate *(W/m²)*	800	58.00	110.00	72.33	11.43
Clothing insulation *(clo)*	800	0.48	1.21	0.74	0.16
Outdoor running mean temp *(α = 0.8) (°C)*	102	-4.60	22.18	10.19	6.98
Thermal comfort votes *(1 out of 7)*	800	1.00	6.00	4.03	0.74
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	800	0.00	1.00	0.75	
Thermally comfortable *(3,4, or 5 sensation)*	800	0.00	1.00	0.95	
Thermally comfortable *(4 sensation)*	800	0.00	1.00	0.60	
Moisture comfort vote *(1 out of 7)*	800	1.00	6.00	3.17	0.99

TABLE APP.A.1 Summary descriptive statistics for C1 W throughout the quasi-experiment

Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	1938	20.75	24.33	22.79	0.84
Relative Humidity (%)	1938	19.52	72.78	42.71	13.43
Lux *(lm/m²)*	1938	27.60	1454.60	446.72	306.73
Metabolic rate *(W/m²)*	832	58.00	110.00	69.00	8.24
Clothing insulation *(clo)*	832	0.40	1.21	0.69	0.15
Outdoor running mean temp *(α = 0.8) (°C)*	102	-4.60	22.18	10.19	6.98
Thermal comfort votes *(1 out of 7)*	832	1.00	7.00	3.99	0.78
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	832	0.00	1.00	0.73	
Thermally comfortable *(3,4, or 5 sensation)*	832	0.00	1.00	0.94	
Thermally comfortable *(4 sensation)*	832	0.00	1.00	0.61	
Moisture comfort vote *(1 out of 7)*	832	1.00	7.00	3.65	0.68

TABLE APP.A.2 Summary descriptive statistics for C1 E throughout the quasi-experiment

Appendix B Room C1 W Weekly Descriptive Statistics

Week 1: No Plants_21.5°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.29	22.35	21.81	0.30
Relative Humidity (%)	114	19.63	28.25	24.73	2.13
Lux *(lm/m^2)*	114	98.50	508.50	241.99	90.50
Metabolic rate *(W/m^2)*	72	58.00	110.00	70.86	11.05
Clothing insulation *(clo)*	72	0.48	0.96	0.78	0.16
Gender *(female votes/total votes)*	72	0.00	1.00	0.28	0.45
Outdoor running mean temp *(α = 0.8) (°C)*	6	-4.24	2.06	-2.13	2.26
Cloud Cover *(okta)*	6	2.00	8.00	6.38	1.93
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	1.00	2.00	1.13 0.00	0.33 1.00
Thermal comfort votes *(1 out of 7)*	72	2.00	6.00	3.85	0.94
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	72	0.00	1.00	0.53	
Thermally comfortable *(3,4, or 5 sensation)*	72	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	72	0.00	1.00	0.43	
Moisture comfort vote *(1 out of 7)*	72	1.00	5.00	3.06	1.03
Week 2: Plants_21.5°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	21.39	22.71	22.01	0.35
Relative Humidity (%)	76	19.94	25.08	22.01	1.38
Lux *(lm/m^2)*	76	185.30	871.20	399.26	170.68
Metabolic rate *(W/m^2)*	49	65.00	90.00	70.61	8.94
Clothing insulation *(clo)*	49	0.57	0.96	0.80	0.14
Gender *(female votes/total votes)*	49	0.00	1.00	0.16	0.37
Outdoor running mean temp *(α = 0.8) (°C)*	4	-4.06	-3.54	-3.80	0.21
Cloud Cover *(okta)*	4	3.00	5.00	4.00	0.71
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	1.00	0.25	0.43
Thermal comfort votes *(1 out of 7)*	49	2.00	6.00	3.94	0.80
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	49	0.00	1.00	0.69	
Thermally comfortable *(3,4, or 5 sensation)*	49	0.00	1.00	0.96	
Thermally comfortable *(4 sensation)*	49	0.00	1.00	0.49	
Moisture comfort vote *(1 out of 7)*	49	1.00	5.00	2.94	1.14
Week 3: Plants_23.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	22.06	22.80	22.42	0.19
Relative Humidity (%)	114	30.70	44.11	37.52	4.21
Lux *(lm/m^2)*	114	122.20	973.60	360.52	255.54
Metabolic rate *(W/m^2)*	61	65.00	110.00	72.05	10.78
Clothing insulation *(clo)*	61	0.48	0.96	0.77	0.17
Gender *(female votes/total votes)*	61	0.00	1.00	0.31	0.47
Outdoor running mean temp *(α = 0.8) (°C)*	6	-1.57	6.79	4.21	3.01
Cloud Cover *(okta)*	6	4.00	8.00	6.13	1.27
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	3.00	3.00	3.00	0.00

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Thermal comfort votes *(1 out of 7)*	61	2.00	5.00	4.00	0.75
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	61	0.00	1.00	0.77	
Thermally comfortable *(3,4, or 5 sensation)*	61	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	61	0.00	1.00	0.54	
Moisture comfort vote *(1 out of 7)*	61	2.00	5.00	3.62	0.66
Week 4: No Plants_23.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	22.49	23.62	23.01	0.28
Relative Humidity (%)	133	18.97	28.07	22.79	2.75
Lux *(lm/m^2)*	133	114.30	1123.40	306.43	194.22
Metabolic rate *(W/m^2)*	84	65.00	90.00	69.88	7.84
Clothing insulation *(clo)*	84	0.48	0.96	0.78	0.17
Gender *(female votes/total votes)*	84	0.00	1.00	0.23	0.42
Outdoor running mean temp *(α = 0.8) (°C)*	7	0.07	6.63	3.24	2.10
Cloud Cover *(okta)*	7	4.00	8.00	5.67	1.25
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	3.00	1.67	1.25
Thermal comfort votes *(1 out of 7)*	84	1.00	6.00	4.40	0.91
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	84	0.00	1.00	0.71	
Thermally comfortable *(3,4, or 5 sensation)*	84	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	84	0.00	1.00	0.40	
Moisture comfort vote *(1 out of 7)*	84	1.00	5.00	2.57	1.13
Week 5: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.65	22.85	21.91	0.19
Relative Humidity (%)	114	18.19	32.00	25.08	4.23
Lux *(lm/m^2)*	114	130.10	1194.40	440.70	317.12
Metabolic rate *(W/m^2)*	65	65.00	110.00	73.69	14.40
Clothing insulation *(clo)*	65	0.48	0.96	0.84	0.14
Gender *(female votes/total votes)*	65	0.00	1.00	0.28	0.45
Outdoor running mean temp *(α = 0.8) (°C)*	6	-0.17	2.86	1.59	1.13
Cloud Cover *(okta)*	6	2.00	8.00	5.13	2.32
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	2.00	0.50	0.87
Thermal comfort votes *(1 out of 7)*	65	2.00	6.00	3.82	0.79
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	65	0.00	1.00	0.60	
Thermally comfortable *(3,4, or 5 sensation)*	65	0.00	1.00	0.95	
Thermally comfortable *(4 sensation)*	65	0.00	1.00	0.49	
Moisture comfort vote *(1 out of 7)*	65	1.00	5.00	2.88	1.11
Week 6: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.51	22.39	21.87	0.18
Relative Humidity (%)	114	19.22	30.47	26.05	3.05
Lux *(lm/m^2)*	114	130.10	697.70	246.89	123.55
Metabolic rate *(W/m^2)*	49	65.00	110.00	73.47	13.55
Clothing insulation *(clo)*	49	0.61	1.21	0.83	0.16
Gender *(female votes/total votes)*	49	0.00	1.00	0.14	0.35
Outdoor running mean temp *(α = 0.8) (°C)*	6	-0.32	1.33	0.51	0.60
Cloud Cover *(okta)*	6	5.00	8.00	7.13	1.27
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	2.00	0.25	0.66

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Thermal comfort votes *(1 out of 7)*	49	2.00	5.00	3.94	0.66
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	49	0.00	1.00	0.69	
Thermally comfortable *(3,4, or 5 sensation)*	49	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	49	0.00	1.00	0.63	
Moisture comfort vote *(1 out of 7)*	49	1.00	5.00	2.33	1.21

TABLE 12.1 Room C1 W Winter Test Session Descriptive Statistics By Week

Week 1: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.84	22.66	22.37	0.18
Relative Humidity (%)	95	33.87	49.70	42.12	4.45
Lux *(lm/m^2)*	95	138.00	642.50	384.29	155.04
Metabolic rate *(W/m^2)*	45	65.00	110.00	75.67	13.92
Clothing insulation *(clo)*	45	0.57	0.96	0.73	0.17
Gender *(female votes/total votes)*	45	0.00	1.00	0.11	0.32
Outdoor running mean temp *(α = 0.8) (°C)*	5	9.96	12.52	11.34	1.01
Cloud Cover *(okta)*	5	1.00	6.00	3.80	1.72
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	45	3.00	5.00	4.00	0.48
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	45	0.00	1.00	0.91	
Thermally comfortable *(3,4, or 5 sensation)*	45	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	45	0.00	1.00	0.78	
Moisture comfort vote *(1 out of 7)*	45	1.00	4.00	3.04	095
Week 2: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	23.08	24.00	23.60	0.27
Relative Humidity (%)	76	28.35	38.85	35.06	3.52
Lux *(lm/m^2)*	76	272.00	484.90	376.32	59.99
Metabolic rate *(W/m^2)*	30	65.00	110.00	72.17	11.27
Clothing insulation *(clo)*	30	0.57	0.96	0.69	0.16
Gender *(female votes/total votes)*	30	0.00	1.00	0.10	0.31
Outdoor running mean temp *(α = 0.8) (°C)*	4	7.96	11.04	9.35	1.09
Cloud Cover *(okta)*	4	0.00	6.00	1.67	2.05
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	30	3.00	6.00	4.33	0.61
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	30	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	30	0.00	1.00		
Thermally comfortable *(4 sensation)*	30	0.00	1.00		
Moisture comfort vote *(1 out of 7)*	30	1.00	4.00	3.23	0.90
Week 3: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	23.26	24.34	23.74	0.28
Relative Humidity (%)	95	33.30	48.37	23.74	4.98
Lux *(lm/m^2)*	95	232.60	729.20	451.02	132.19
Metabolic rate *(W/m^2)*	31	65.00	90.00	70.65	7.93
Clothing insulation *(clo)*	31	0.57	0.96	0.72	0.17
Gender *(female votes/total votes)*	31	0.00	1.00	0.16	0.37

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Outdoor running mean temp *(α = 0.8) (°C)*	5	10.77	13.76	12.44	0.97
Cloud Cover *(okta)*	5	4.00	7.00	5.78	1.23
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.33	1.49
Thermal comfort votes *(1 out of 7)*	31	3.00	6.00	4.45	0.81
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	31	0.00	1.00	0.74	
Thermally comfortable *(3,4, or 5 sensation)*	31	0.00	1.00	0.87	
Thermally comfortable *(4 sensation)*	31	0.00	1.00	0.55	
Moisture comfort vote *(1 out of 7)*	31	1.00	4.00	3.39	0.84
Week 4: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.89	22.82	22.32	0.28
Relative Humidity (%)	114	30.07	46.50	38.51	4.70
Lux *(lm/m²)*	114	130.10	642.50	342.79	148.23
Metabolic rate *(W/m²)*	49	65.00	110.00	72.96	11.36
Clothing insulation *(clo)*	49	0.57	0.96	0.75	0.18
Gender *(female votes/total votes)*	49	0.00	1.00	0.14	0.35
Outdoor running mean temp *(α = 0.8) (°C)*	6	9.04	10.60	9.77	9.77
Cloud Cover *(okta)*	6	5.00	8.00	6.89	6.89
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	3.00	1.67	1.67
Thermal comfort votes *(1 out of 7)*	49	2.00	5.00	3.78	0.62
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	49	0.00	1.00	0.76	
Thermally comfortable *(3,4, or 5 sensation)*	49	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	49	0.00	1.00	0.63	
Moisture comfort vote *(1 out of 7)*	49	2.00	4.00	3.31	0.80

TABLE 12.2 Room C1 W spring test session descriptive statistics by week

Week 1: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.82	22.49	22.17	0.20
Relative Humidity (%)	95	37.65	58.73	45.36	7.16
Lux *(lm/m²)*	95	201.00	792.30	388.28	173.38
Metabolic rate *(W/m²)*	28	65.00	90.00	70.36	9.02
Clothing insulation *(clo)*	28	0.48	0.96	0.75	0.18
Gender *(female votes/total votes)*	28	0.00	1.00	0.21	0.42
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.19	15.29	14.77	0.42
Cloud Cover *(okta)*	5	3.00	8.00	6.40	1.85
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.20	1.47
Thermal comfort votes *(1 out of 7)*	28	0.00	1.00	3.57	0.74
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	28	0.00	1.00	0.68	
Thermally comfortable *(3,4, or 5 sensation)*	28	0.00	1.00	0.93	
Thermally comfortable *(4 sensation)*	28	0.00	1.00	0.50	
Moisture comfort vote *(1 out of 7)*	28	2.00	4.00	3.36	0.87
Week 2: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	23.21	24.51	23.74	0.35
Relative Humidity (%)	133	38.58	65.05	54.75	8.47
Lux *(lm/m²)*	133	169.50	745.00	399.78	178.85

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Metabolic rate *(W/m²)*	43	58.00	110.00	69.84	9.15
Clothing insulation *(clo)*	43	0.57	0.96	0.68	0.15
Gender *(female votes/total votes)*	43	0.00	1.00	0.19	0.39
Outdoor running mean temp *(α = 0.8) (°C)*	7	13.55	18.78	15.82	1.66
Cloud Cover *(okta)*	7	3.00	8.00	6.17	1.67
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	3.00	1.17	1.46
Thermal comfort votes *(1 out of 7)*	43	3.00	6.00	4.30	0.64
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	43	0.00	1.00	0.74	
Thermally comfortable *(3,4, or 5 sensation)*	43	0.00	1.00	0.95	
Thermally comfortable *(4 sensation)*	43	0.00	1.00	0.65	
Moisture comfort vote *(1 out of 7)*	43	2.00	6.00	3.56	0.91
Week 3: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	152	23.14	24.17	23.53	0.23
Relative Humidity (%)	152	40.80	59.82	50.82	6.12
Lux *(lm/m²)*	152	208.90	366.60	261.91	39.17
Metabolic rate *(W/m²)*	43	65.00	110.00	73.84	11.79
Clothing insulation *(clo)*	43	0.57	0.96	0.61	0.06
Gender *(female votes/total votes)*	43	0.00	1.00	0.02	0.15
Outdoor running mean temp *(α = 0.8) (°C)*	8	16.15	18.66	17.28	0.91
Cloud Cover *(okta)*	8	0.00	7.00	2.82	2.34
Precipitation *(1:snow on ground;2:snowing;3:rain)*	8	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	43	3.00	5.00	4.07	0.46
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	43	0.00	1.00	0.98	
Thermally comfortable *(3,4, or 5 sensation)*	43	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	43	0.00	1.00	0.79	
Moisture comfort vote *(1 out of 7)*	43	2.00	4.00	3.30	0.56
Week 4: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	22.52	23.88	22.94	0.36
Relative Humidity (%)	133	50.85	71.10	61.46	6.00
Lux *(lm/m²)*	133	212.80	544.80	366.68	107.72
Metabolic rate *(W/m²)*	26	65.00	110.00	72.88	12.58
Clothing insulation *(clo)*	26	0.57	0.61	0.59	0.02
Gender *(female votes/total votes)*	26	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	7	16.82	22.18	19.50	16.82
Cloud Cover *(okta)*	7	0.00	5.00	2.11	0.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	49	3.00	5.00	4.04	0.60
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	49	0.00	1.00	0.77	
Thermally comfortable *(3,4, or 5 sensation)*	49	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	49	0.00	1.00	0.65	
Moisture comfort vote *(1 out of 7)*	49	3.00	5.00	3.50	0.58

TABLE APP.B.1 Room C1 W summer test session descriptive statistics by week

Week 1: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.13	23.09	22.52	0.21
Relative Humidity (%)	95	57.25	70.00	65.76	4.28
Lux *(lm/m²)*	95	114.30	406.00	286.99	57.77
Metabolic rate *(W/m²)*	31	65.00	90.00	71.29	7.85
Clothing insulation *(clo)*	31	0.57	0.86	0.61	0.05
Gender *(female votes/total votes)*	31	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	5	16.48	19.39	17.47	1.09
Cloud Cover *(okta)*	5	0.00	4.00	2.60	1.50
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	31	3.00	5.00	4.00	0.26
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	31	0.00	1.00	0.97	
Thermally comfortable *(3,4, or 5 sensation)*	31	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	31	0.00	1.00	0.94	
Moisture comfort vote *(1 out of 7)*	31	3.00	5.00	3.74	0.63

Week 2: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	23.18	23.83	23.46	0.20
Relative Humidity (%)	95	47.49	55.37	51.41	2.35
Lux *(lm/m2)*	95	74.90	350.80	220.77	57.05
Metabolic rate *(W/m2)*	20	65.00	110.00	77.00	14.82
Clothing insulation *(clo)*	20	0.57	0.96	0.67	0.13
Gender *(female votes/total votes)*	20	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.60	17.96	15.90	1.19
Cloud Cover *(okta)*	5	6.00	7.00	6.80	0.40
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	3.00	3.00	3.00	0.00
Thermal comfort votes *(1 out of 7)*	20	3.00	5.00	4.05	0.39
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	20	0.00	1.00	0.90	
Thermally comfortable *(3,4, or 5 sensation)*	20	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	20	0.00	1.00	0.85	
Moisture comfort vote *(1 out of 7)*	20	2.00	5.00	3.55	0.69

Week 3: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	23.11	23.79	23.42	0.19
Relative Humidity (%)	95	35.98	49.66	42.03	4.14
Lux *(lm/m²)*	95	240.50	1383.60	471.16	287.10
Metabolic rate *(W/m²)*	42	65.00	110.00	76.31	13.44
Clothing insulation *(clo)*	42	0.57	0.96	9.65	0.10
Gender *(female votes/total votes)*	42	0.00	1.00	0.05	0.22
Outdoor running mean temp *(α = 0.8) (°C)*	5	12.47	14.08	13.09	0.64
Cloud Cover *(okta)*	5	5.00	7.00	6.60	0.80
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	2.40	1.20
Thermal comfort votes *(1 out of 7)*	42	3.00	6.00	4.07	0.60
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	42	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	42	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	42	0.00	1.00	0.71	
Moisture comfort vote *(1 out of 7)*	42	2.00	5.00	3.48	0.63

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Week 4: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.96	22.87	22.28	0.19
Relative Humidity (%)	95	43.65	65.31	57.73	6.40
Lux *(lm/m²)*	95	279.90	698.50	427.72	96.72
Metabolic rate *(W/m²)*	32	65.00	110.00	72.19	13.07
Clothing insulation *(clo)*	32	0.48	0.96	0.69	0.15
Gender *(female votes/total votes)*	32	0.00	1.00	0.06	0.25
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.06	15.23	14.80	14.80
Cloud Cover *(okta)*	5	1.00	7.00	5.00	5.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	32	2.00	5.00	3.88	0.49
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	32	0.00	1.00	0.88	
Thermally comfortable *(3,4, or 5 sensation)*	32	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	32	0.00	1.00	0.84	
Moisture comfort vote *(1 out of 7)*	32	3.00	5.00	3.69	0.54

TABLE APP.B.2 Room C1 W fall test session descriptive statistics by week

Appendix C

Room C1 E Weekly Descriptive Statistics

Week 1: Plants_21.5°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	20.75	21.92	21.40	0.32
Relative Humidity (%)	114	22.36	33.64	26.41	2.54
Lux *(lm/m²)*	114	90.70	745.00	285.57	164.52
Metabolic rate *(W/m²)*	58	58.00	110.00	71.83	12.77
Clothing insulation *(clo)*	58	0.48	1.21	0.82	0.17
Gender *(female votes/total votes)*	58	0.00	1.00	0.5	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	6	-4.24	2.06	-2.13	2.26
Cloud Cover *(okta)*	6	2.00	8.00	6.38	1.93
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	1.00	2.00	1.13	0.33
Thermal comfort votes *(1 out of 7)*	58	1.00	5.00	3.79	0.50
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	58	0.00	1.00	0.67	
Thermally comfortable *(3,4, or 5 sensation)*	58	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	58	0.00	1.00	0.64	
Moisture comfort vote *(1 out of 7)*	58	1.00	5.00	3.59	0.73
Week 2: No Plants_21.5°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	21.01	22.06	21.62	0.31
Relative Humidity (%)	76	20.53	25.83	23.36	1.69
Lux *(lm/m²)*	76	138.00	1202.00	600.65	295.77
Metabolic rate *(W/m²)*	32	65.00	110.00	72.19	10.39
Clothing insulation *(clo)*	32	0.61	0.96	0.82	0.13
Gender *(female votes/total votes)*	32	0.00	1.00	050	0.51
Outdoor running mean temp *(α = 0.8) (°C)*	4	-4.06	-3.54	-3.80	0.21
Cloud Cover *(okta)*	4	3.00	5.00	4.00	0.71
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	2.00	0.25	0.43
Thermal comfort votes *(1 out of 7)*	32	2.00	5.00	3.69	0.43
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	32	0.00	1.00	0.59	
Thermally comfortable *(3,4, or 5 sensation)*	32	0.00	1.00	0.94	
Thermally comfortable *(4 sensation)*	32	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	32	2.00	5.00	3.53	0.72
Week 3: No Plants_23.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	22.11	22.99	22.49	0.19
Relative Humidity (%)	114	32.01	45.58	38.07	4.57
Lux *(lm/m²)*	114	74.90	855.40	384.03	251.76
Metabolic rate *(W/m²)*	57	65.00	90.00	69.12	5.60
Clothing insulation *(clo)*	57	0.48	0.96	0.79	0.14
Gender *(female votes/total votes)*	57	0.00	1.00	0.54	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	6	-1.57	6.79	4.21	3.01
Cloud Cover *(okta)*	6	4.00	8.00	6.13	1.27
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	3.00	3.00	3.00	3.00

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Thermal comfort votes *(1 out of 7)*	57	3.00	6.00	4.21	0.86
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	57	0.00	1.00	0.68	
Thermally comfortable *(3,4, or 5 sensation)*	57	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	57	0.00	1.00	0.54	
Moisture comfort vote *(1 out of 7)*	57	2.00	5.00	3.82	0.71
Week 4: Plants_23.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	21.72	23.21	22.61	0.35
Relative Humidity (%)	133	21.67	30.52	26.06	2.79
Lux *(lm/m²)*	133	59.10	784.40	316.88	238.47
Metabolic rate *(W/m²)*	46	65.00	110.00	71.52	9.12
Clothing insulation *(clo)*	46	0.48	1.21	0.84	0.17
Gender *(female votes/total votes)*	46	0.00	1.00	0.54	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	7	0.07	6.63	3.24	2.10
Cloud Cover *(okta)*	7	4.00	8.00	5.67	1.25
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	3.00	1.67	1.25
Thermal comfort votes *(1 out of 7)*	46	1.00	5.00	3.91	0.69
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	46	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	46	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	46	0.00	1.00	0.70	
Moisture comfort vote *(1 out of 7)*	46	2.00	5.00	3.59	0.81
Week 5: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.53	22.59	22.18	0.29
Relative Humidity (%)	114	20.83	34.86	28.28	4.11
Lux *(lm/m²)*	114	98.50	1194.40	327.65	267.22
Metabolic rate *(W/m²)*	33	65.00	75.00	66.82	3.92
Clothing insulation *(clo)*	33	0.48	0.96	0.75	0.16
Gender *(female votes/total votes)*	33	0.00	1.00	0.45	0.51
Outdoor running mean temp *(α = 0.8) (°C)*	6	-0.17	2.86	1.59	1.13
Cloud Cover *(okta)*	6	2.00	8.00	5.13	2.32
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	2.00	0.50	0.87
Thermal comfort votes *(1 out of 7)*	33	1.00	5.00	3.76	0.71
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	33	0.00	1.00	0.76	
Thermally comfortable *(3,4, or 5 sensation)*	33	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	33	0.00	1.00	0.70	
Moisture comfort vote *(1 out of 7)*	33	2.00	5.00	3.45	0.75
Week 6: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.65	22.75	22.17	0.28
Relative Humidity (%)	114	19.52	30.53	27.51	2.43
Lux *(lm/m²)*	114	114.30	1091.90	397.79	271.43
Metabolic rate *(W/m²)*	48	65.00	90.00	68.54	7.44
Clothing insulation *(clo)*	48	0.48	1.21	0.84	0.14
Gender *(female votes/total votes)*	48	0.00	1.00	0.71	0.46
Outdoor running mean temp *(α = 0.8) (°C)*	6	-0.32	1.33	0.51	0.60
Cloud Cover *(okta)*	6	5.00	8.00	7.13	1.27
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	2.00	0.25	0.66

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Thermal comfort votes *(1 out of 7)*	48	2.00	5.00	3.60	0.71
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	48	0.00	1.00	0.65	
Thermally comfortable *(3,4, or 5 sensation)*	48	0.00	1.00	0.94	
Thermally comfortable *(4 sensation)*	48	0.00	1.00	0.54	
Moisture comfort vote *(1 out of 7)*	48	2.00	5.00	3.69	0.62

TABLE APP.C.1 Room C1 E Winter Test Session Descriptive Statistics By Week

Week 1: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.23	22.97	22.56	0.21
Relative Humidity (%)	95	35.09	49.25	42.76	4.26
Lux *(lm/m²)*	95	185.30	1454.60	566.04	425.88
Metabolic rate *(W/m²)*	37	65.00	100.00	73.51	13.79
Clothing insulation *(clo)*	37	0.48	0.96	0.64	0.10
Gender *(female votes/total votes)*	37	0.00	1.00	0.57	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	5	9.96	12.52	11.34	1.01
Cloud Cover *(okta)*	5	1.00	6.00	3.80	1.72
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	37	2.00	7.00	4.32	0.92
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	37	0.00	1.00	0.57	
Thermally comfortable *(3,4, or 5 sensation)*	37	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	37	0.00	1.00	0.54	
Moisture comfort vote *(1 out of 7)*	37	2.00	4.00	3.57	0.56
Week 2: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	23.35	24.20	23.76	0.26
Relative Humidity (%)	76	29.07	38.38	34.10	3.25
Lux *(lm/m²)*	76	193.20	1139.20	619.74	334.21
Metabolic rate *(W/m²)*	45	65.00	90.00	67.00	5.78
Clothing insulation *(clo)*	45	0.40	0.86	0.66	0.12
Gender *(female votes/total votes)*	45	0.00	1.00	0.69	0.47
Outdoor running mean temp *(α = 0.8) (°C)*	4	7.96	11.04	9.35	1.09
Cloud Cover *(okta)*	4	0.00	6.00	1.67	2.05
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	45	3.00	6.00	4.60	0.72
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	45	0.00	1.00	0.60	
Thermally comfortable *(3,4, or 5 sensation)*	45	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	45	0.00	1.00	0.47	
Moisture comfort vote *(1 out of 7)*	45	2.00	4.00	3.51	0.70
Week 3: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	23.40	24.33	23.93	0.19
Relative Humidity (%)	76	33.94	52.12	41.27	5.01
Lux *(lm/m²)*	76	106.40	1052.50	530.18	289.07
Metabolic rate *(W/m²)*	68	58.00	110.00	69.60	10.04
Clothing insulation *(clo)*	68	0.40	0.96	0.67	0.13
Gender *(female votes/total votes)*	68	0.00	1.00	0.62	0.49

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Outdoor running mean temp *(α = 0.8) (°C)*	5	10.77	13.76	12.44	0.97
Cloud Cover *(okta)*	5	4.00	7.00	5.78	1.23
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.33	1.49
Thermal comfort votes *(1 out of 7)*	68	3.00	7.00	4.49	0.74
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	68	0.00	1.00	0.78	
Thermally comfortable *(3,4, or 5 sensation)*	68	0.00	1.00	0.93	
Thermally comfortable *(4 sensation)*	68	0.00	1.00	0.51	
Moisture comfort vote *(1 out of 7)*	68	2.00	5.00	3.75	0.61
Week 4: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.56	22.47	22.06	0.18
Relative Humidity (%)	114	33.25	48.02	41.16	4.50
Lux *(lm/m²)*	114	90.70	1131.30	405.28	338.89
Metabolic rate *(W/m²)*	54	58.00	90.00	68.76	8.28
Clothing insulation *(clo)*	54	0.48	0.96	0.67	0.14
Gender *(female votes/total votes)*	54	0.00	1.00	0.46	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	6	9.04	10.60	9.77	9.77
Cloud Cover *(okta)*	6	5.00	8.00	6.89	6.89
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	3.00	1.67	1.67
Thermal comfort votes *(1 out of 7)*	54	2.00	4.00	3.63	0.59
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	54	0.00	1.00	0.80	
Thermally comfortable *(3,4, or 5 sensation)*	54	0.00	1.00	0.94	
Thermally comfortable *(4 sensation)*	54	0.00	1.00	0.69	
Moisture comfort vote *(1 out of 7)*	54	2.00	5.00	3.67	0.67

TABLE APP.C.2 Room C1 E spring test session descriptive statistics by week

Week 1: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.99	22.59	22.26	0.13
Relative Humidity (%)	95	40.35	60.07	48.81	7.18
Lux *(lm/m²)*	95	161.60	1218.00	560.73	353.40
Metabolic rate *(W/m²)*	32	65.00	90.00	69.38	8.59
Clothing insulation *(clo)*	32	0.57	0.86	0.64	0.08
Gender *(female votes/total votes)*	32	0.00	1.00	0.38	0.49
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.19	15.29	14.77	0.42
Cloud Cover *(okta)*	5	3.00	8.00	6.40	1.85
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.20	1.47
Thermal comfort votes *(1 out of 7)*	32	3.00	4.00	3.84	0.37
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	32	0.00	1.00	0.81	
Thermally comfortable *(3,4, or 5 sensation)*	32	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	32	0.00	1.00	0.84	
Moisture comfort vote *(1 out of 7)*	32	2.00	4.00	3.56	0.62
Week 2: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	23.16	24.16	23.86	0.23
Relative Humidity (%)	133	40.63	66.72	54.84	9.05
Lux *(lm/m²)*	133	106.40	1068.20	514.23	315.21

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Metabolic rate *(W/m^2)*	44	65.00	90.00	68.52	7.04
Clothing insulation *(clo)*	44	0.40	0.96	0.61	0.08
Gender *(female votes/total votes)*	44	0.00	1.00	0.39	0.49
Outdoor running mean temp *(α = 0.8) (°C)*	7	13.55	14.83	14.04	0.49
Cloud Cover *(okta)*	7	4.00	8.00	6.33	1.25
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	3.00	1.00	1.41
Thermal comfort votes *(1 out of 7)*	44	3.00	6.00	4.02	0.66
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	44	0.00	1.00	0.82	
Thermally comfortable *(3,4, or 5 sensation)*	44	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	44	0.00	1.00	0.64	
Moisture comfort vote *(1 out of 7)*	44	1.00	7.00	3.57	1.00
Week 3: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	152	23.50	24.10	23.85	0.13
Relative Humidity (%)	152	42.03	59.38	51.66	5.57
Lux *(lm/m^2)*	152	208.90	1218.00	645.62	332.87
Metabolic rate *(W/m^2)*	61	65.00	90.00	67.54	5.05
Clothing insulation *(clo)*	61	0.40	0.96	0.59	0.09
Gender *(female votes/total votes)*	61	0.00	1.00	0.36	0.48
Outdoor running mean temp *(α = 0.8) (°C)*	8	14.88	18.66	16.97	1.32
Cloud Cover *(okta)*	8	0.00	8.00	3.11	3.07
Precipitation *(1:snow on ground;2:snowing;3:rain)*	8	0.00	3.00	0.67	1.25
Thermal comfort votes *(1 out of 7)*	61	2.00	6.00	4.26	0.79
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	61	0.00	1.00	0.77	
Thermally comfortable *(3,4, or 5 sensation)*	61	0.00	1.00	0.92	
Thermally comfortable *(4 sensation)*	61	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	61	2.00	4.00	3.54	0.57
Week 4: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	22.35	23.86	22.93	0.34
Relative Humidity (%)	133	50.84	72.78	62.07	6.04
Lux *(lm/m^2)*	133	93.20	1233.80	465.12	321.16
Metabolic rate *(W/m^2)*	55	65.00	90.00	67.73	5.84
Clothing insulation *(clo)*	55	0.40	0.96	0.58	0.10
Gender *(female votes/total votes)*	55	0.00	1.00	0.44	0.50
Outdoor running mean temp *(α = 0.8) (°C)*	7	16.15	19.20	17.30	17.30
Cloud Cover *(okta)*	7	0.00	7.00	3.33	3.33
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	55	2.00	7.00	3.93	0.96
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	55	0.00	1.00	0.76	
Thermally comfortable *(3,4, or 5 sensation)*	55	0.00	1.00	0.89	
Thermally comfortable *(4 sensation)*	55	0.00	1.00	0.60	
Moisture comfort vote *(1 out of 7)*	55	2.00	6.00	3.82	0.67

TABLE APP.C.3 Room C1 E summer test session descriptive statistics by week

Week 1: No Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.15	23.02	22.39	0.17
Relative Humidity (%)	95	58.50	71.08	66.51	4.03
Lux *(lm/m²)*	95	27.60	760.80	393.72	200.05
Metabolic rate *(W/m²)*	34	58.00	90.00	69.06	9.23
Clothing insulation *(clo)*	34	0.57	0.96	0.65	0.13
Gender *(female votes/total votes)*	34	0.00	1.00	0.53	0.51
Outdoor running mean temp *(α = 0.8) (°C)*	5	16.48	19.39	17.47	1.09
Cloud Cover *(okta)*	5	0.00	4.00	2.60	1.50
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	34	3.00	5.00	3.91	0.71
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	34	0.00	1.00	0.74	
Thermally comfortable *(3,4, or 5 sensation)*	34	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	34	0.00	1.00	0.50	
Moisture comfort vote *(1 out of 7)*	34	2.00	5.00	3.68	0.68

Week 2: No Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.96	24.00	23.41	0.27
Relative Humidity (%)	95	48.47	56.21	52.28	2.14
Lux *(lm/m²)*	95	130.10	1068.20	375.93	272.00
Metabolic rate *(W/m²)*	54	58.00	110.00	70.49	12.07
Clothing insulation *(clo)*	54	40.00	0.96	0.67	0.13
Gender *(female votes/total votes)*	54	0.00	1.00	0.62	0.49
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.60	17.96	15.90	1.19
Cloud Cover *(okta)*	5	6.00	7.00	6.80	0.40
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	3.00	3.00	3.00	0.00
Thermal comfort votes *(1 out of 7)*	54	2.00	6.00	4.17	0.75
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	54	0.00	1.00	0.70	
Thermally comfortable *(3,4, or 5 sensation)*	54	0.00	1.00	0.91	
Thermally comfortable *(4 sensation)*	54	0.00	1.00	0.70	
Moisture comfort vote *(1 out of 7)*	54	2.00	5.00	3.59	0.60

Week 3: Plants_25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	23.22	23.99	23.47	0.20
Relative Humidity (%)	95	38.30	51.47	44.16	3.51
Lux *(lm/m²)*	95	114.30	792.30	329.58	198.11
Metabolic rate *(W/m²)*	36	65.00	90.00	67.50	6.38
Clothing insulation *(clo)*	36	0.48	0.96	0.70	0.16
Gender *(female votes/total votes)*	36	0.00	1.00	0.47	0.51
Outdoor running mean temp *(α = 0.8) (°C)*	5	12.47	14.08	13.09	0.64
Cloud Cover *(okta)*	5	5.00	7.00	6.60	0.80
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	2.40	1.20
Thermal comfort votes *(1 out of 7)*	36	3.00	5.00	4.17	0.51
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	36	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	36	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	36	0.00	1.00	0.72	
Moisture comfort vote *(1 out of 7)*	36	3.00	5.00	3.86	0.49

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Week 4: Plants_22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.80	22.39	22.11	0.16
Relative Humidity (%)	95	46.49	67.04	59.88	6.23
Lux *(lm/m²)*	95	130.10	697.70	306.84	166.43
Metabolic rate *(W/m²)*	38	65.00	110.00	68.55	9.29
Clothing insulation *(clo)*	38	0.48	0.96	0.66	0.13
Gender *(female votes/total votes)*	38	0.00	1.00	0.47	0.51
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.06	15.23	14.80	14.80
Cloud Cover *(okta)*	5	1.00	7.00	5.00	5.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	38	2.00	5.00	3.66	0.58
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	38	0.00	1.00	0.82	
Thermally comfortable *(3,4, or 5 sensation)*	38	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	38	0.00	1.00	0.63	
Moisture comfort vote *(1 out of 7)*	38	2.00	5.00	3.71	0.57

TABLE APP.C.4 Room C1 E fall test session descriptive statistics by week

Appendix D Room E1 Weekly Descriptive Statistics

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.08	22.42	21.57	0.42
Relative Humidity (%)	95	21.97	28.64	25.58	1.94
Lux *(lm/m²)*	95	114.30	871.15	253.53	198.23
Metabolic rate *(W/m²)*	41	65.00	90.00	72.56	8.67
Clothing insulation *(clo)*	41	0.61	0.96	0.78	0.13
Gender *(female votes/total votes)*	41	0.00	1.00	0.07	0.26
Outdoor running mean temp *(α = 0.8) (°C)*	5	-4.10	2.06	-1.02	2.21
Cloud Cover *(okta)*	5	2.00	8.00	5.80	2.14
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	1.00	1.00	1.00	1.00
Thermal comfort votes *(1 out of 7)*	41	2.00	5.00	3.71	0.64
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	41	0.00	1.00	0.68	
Thermally comfortable *(3,4, or 5 sensation)*	41	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	41	0.00	1.00	0.59	
Moisture comfort vote *(1 out of 7)*	41	1.00	4.00	3.51	0.78
Week 2-5: 21.5°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	342	20.90	22.80	21.47	0.38
Relative Humidity (%)	342	22.19	47.72	30.77	7.76
Lux *(lm/m²)*	342	106.40	2345.40	440.06	417.43
Metabolic rate *(W/m²)*	102	58.00	100.00	71.35	9.37
Clothing insulation *(clo)*	102	0.57	0.96	0.81	0.12
Gender *(female votes/total votes)*	102	0.00	1.00	0.18	0.38
Outdoor running mean temp *(α = 0.8) (°C)*	18	-4.60	6.9	1.64	3.96
Cloud Cover *(okta)*	18	3.00	8.00	5.63	1.38
Precipitation *(1:snow on ground;2:snowing;3:rain)*	18	0.00	3.00	2.00	1.26
Thermal comfort votes *(1 out of 7)*	102	2.00	5.00	3.58	0.61
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	102	0.00	1.00	0.60	
Thermally comfortable *(3,4, or 5 sensation)*	102	0.00	1.00	0.98	
Thermally comfortable *(4 sensation)*	102	0.00	1.00	0.52	
Moisture comfort vote *(1 out of 7)*	102	2.00	5.00	3.73	0.55
Week 6: 23.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	22.00	23.71	22.65	0.40
Relative Humidity (%)	114	20.77	35.58	30.44	4.57
Lux *(lm/m²)*	114	161.60	867.25	472.35	260.34
Metabolic rate *(W/m²)*	29	65.00	90.00	74.14	10.10
Clothing insulation *(clo)*	29	0.57	0.96	0.77	0.14
Gender *(female votes/total votes)*	29	0.00	1.00	0.14	0.35
Outdoor running mean temp *(α = 0.8) (°C)*	5	-0.17	2.86	1.77	0.95
Cloud Cover *(okta)*	5	2.00	8.00	4.88	2.20
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	2.00	0.25	0.66

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Thermal comfort votes *(1 out of 7)*	29	2.00	5.00	4.00	0.60
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	29	0.00	1.00	0.93	
Thermally comfortable *(3,4, or 5 sensation)*	29	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	29	0.00	1.00	0.76	
Moisture comfort vote *(1 out of 7)*	29	2.00	4.00	3.62	0.68

TABLE APP.D.1 Room E1 winter test session descriptive statistics by week

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.58	23.26	22.68	0.33
Relative Humidity (%)	95	35.61	50.69	44.11	4.64
Lux *(lm/m²)*	95	177.40	831.70	436.59	204.07
Metabolic rate *(W/m²)*	41	65.00	110.00	72.56	12.41
Clothing insulation *(clo)*	41	0.48	0.96	0.68	0.13
Gender *(female votes/total votes)*	41	0.00	1.00	0.07	0.26
Outdoor running mean temp *(α = 0.8) (°C)*	5	9.96	12.52	11.34	1.01
Cloud Cover *(okta)*	5	1.00	6.00	3.80	1.72
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	41	2.00	5.00	4.00	0.63
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	41	0.00	1.0	0.88	
Thermally comfortable *(3,4, or 5 sensation)*	41	0.00	1.0	0.98	
Thermally comfortable *(4 sensation)*	41	0.00	1.0	0.68	
Moisture comfort vote *(1 out of 7)*	41	3.00	5.00	3.76	0.49
Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	171	22.60	24.05	23.23	0.47
Relative Humidity (%)	171	31.16	54.32	39.70	4.74
Lux *(lm/m²)*	171	208.90	965.80	525.71	192.35
Metabolic rate *(W/m²)*	52	65.00	110.00	76.15	11.32
Clothing insulation *(clo)*	52	0.57	0.96	0.70	0.14
Gender *(female votes/total votes)*	52	0.00	1.00	0.08	0.27
Outdoor running mean temp *(α = 0.8) (°C)*	9	7.96	13.76	11.20	1.83
Cloud Cover *(okta)*	9	0.00	7.00	4.13	2.58
Precipitation *(1:snow on ground;2:snowing;3:rain)*	9	0.00	3.00	0.80	1.33
Thermal comfort votes *(1 out of 7)*	52	3.00	5.00	4.15	0.46
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	52	0.00	1.00	0.87	
Thermally comfortable *(3,4, or 5 sensation)*	52	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	52	0.00	1.00	0.77	
Moisture comfort vote *(1 out of 7)*	52	3.00	4.00	3.83	0.38
Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.56	22.97	22.16	0.41
Relative Humidity (%)	114	34.27	50.42	40.98	4.34
Lux *(lm/m²)*	114	153.70	658.30	431.45	239.33
Metabolic rate *(W/m²)*	31	58.00	110.00	75.26	14.45
Clothing insulation *(clo)*	31	0.57	0.96	0.73	0.15
Gender *(female votes/total votes)*	31	0.00	1.00	0.16	0.37

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Outdoor running mean temp *(α = 0.8) (°C)*	6	9.04	10.60	9.77	9.04
Cloud Cover *(okta)*	6	5.00	8.00	6.89	5.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	3.00	1.67	0.00
Thermal comfort votes *(1 out of 7)*	31	3.00	4.00	3.77	0.43
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	31	0.00	1.00	0.84	
Thermally comfortable *(3,4, or 5 sensation)*	31	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	31	0.00	1.00	0.77	
Moisture comfort vote *(1 out of 7)*	31	3.00	4.00	3.94	0.25

TABLE APP.D.2 Room E1 spring test session descriptive statistics by week

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.44	22.97	22.42	0.34
Relative Humidity (%)	95	40.56	59.25	50.47	6.50
Lux *(lm/m²)*	95	141.90	626.75	361.87	150.89
Metabolic rate *(W/m²)*	31	65.00	110.00	73.33	14.70
Clothing insulation *(clo)*	31	0.57	0.86	0.64	0.10
Gender *(female votes/total votes)*	31	0.00	1.00	0.23	0.43
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.19	15.29	14.77	0.42
Cloud Cover *(okta)*	5	3.00	8.00	6.40	1.85
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.20	1.47
Thermal comfort votes *(1 out of 7)*	31	2.00	5.00	3.77	0.77
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	31	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	31	0.00	1.00	0.93	
Thermally comfortable *(4 sensation)*	31	0.00	1.00	0.57	
Moisture comfort vote *(1 out of 7)*	31	3.00	6.00	4.30	0.75
Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	285	23.23	24.48	23.72	0.29
Relative Humidity (%)	285	42.00	69.05	55.00	7.70
Lux *(lm/m²)*	285	153.70	698.80	426.29	139.42
Metabolic rate *(W/m²)*	83	65.00	110.00	73.73	10.87
Clothing insulation *(clo)*	83	0.57	86.00	0.59	0.06
Gender *(female votes/total votes)*	83	0.00	1.00	0.10	0.30
Outdoor running mean temp *(α = 0.8) (°C)*	15	13.55	18.78	16.30	1.54
Cloud Cover *(okta)*	15	0.00	8.00	4.79	2.46
Precipitation *(1:snow on ground;2:snowing;3:rain)*	15	0.00	3.00	0.64	1.23
Thermal comfort votes *(1 out of 7)*	83	2.00	6.00	4.10	0.62
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	83	0.00	1.00	0.87	
Thermally comfortable *(3,4, or 5 sensation)*	83	0.00	1.00	0.96	
Thermally comfortable *(4 sensation)*	83	0.00	1.00	0.72	
Moisture comfort vote *(1 out of 7)*	83	3.00	7.00	4.20	0.68
Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	22.39	23.96	23.03	0.37
Relative Humidity (%)	133	54.38	69.32	62.37	4.64
Lux *(lm/m²)*	133	225.20	697.70	478.62	114.70

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Metabolic rate *(W/m²)*	33	65.00	110.00	73.48	12.02
Clothing insulation *(clo)*	33	0.57	0.61	0.59	0.02
Gender *(female votes/total votes)*	33	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	7	16.82	22.18	19.50	16.82
Cloud Cover *(okta)*	7	0.00	5.00	2.11	0.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	33	3.00	7.00	3.97	0.73
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	33	0.00	1.00	0.85	
Thermally comfortable *(3,4, or 5 sensation)*	33	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	33	0.00	1.00	0.73	
Moisture comfort vote *(1 out of 7)*	33	3.00	6.00	4.27	0.57

TABLE APP.D.3 Room E1 summer test session descriptive statistics by week

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.84	24.00	23.35	0.34
Relative Humidity (%)	95	58.89	69.43	64.81	3.15
Lux *(lm/m²)*	95	122.20	879.00	441.08	233.36
Metabolic rate *(W/m²)*	28	65.00	90.00	71.61	8.06
Clothing insulation *(clo)*	28	0.57	0.96	0.63	0.11
Gender *(female votes/total votes)*	28	0.00	1.00	0.21	0.42
Outdoor running mean temp *(α = 0.8) (°C)*	5	16.48	19.39	17.47	1.09
Cloud Cover *(okta)*	5	0.00	4.00	2.60	1.50
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	28	3.00	5.00	4.11	0.50
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	28	0.00	1.00	0.96	
Thermally comfortable *(3,4, or 5 sensation)*	28	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	28	0.00	1.00	0.75	
Moisture comfort vote *(1 out of 7)*	28	4.00	6.00	4.29	0.66
Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	190	22.67	24.82	23.30	0.38
Relative Humidity (%)	190	38.62	60.32	48.91	5.70
Lux *(lm/m²)*	190	126.15	894.80	321.83	199.94
Metabolic rate *(W/m²)*	57	65.00	110.00	73.51	9.73
Clothing insulation *(clo)*	57	0.57	0.96	0.68	0.15
Gender *(female votes/total votes)*	57	0.00	1.00	0.21	0.41
Outdoor running mean temp *(α = 0.8) (°C)*	10	12.47	17.96	14.48	1.55
Cloud Cover *(okta)*	10	5.00	7.00	6.67	0.62
Precipitation *(1:snow on ground;2:snowing;3:rain)*	10	0.00	3.00	2.75	0.83
Thermal comfort votes *(1 out of 7)*	57	3.00	5.00	3.98	0.52
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	57	0.00	1.00	0.93	
Thermally comfortable *(3,4, or 5 sensation)*	57	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	57	0.00	1.00	0.74	
Moisture comfort vote *(1 out of 7)*	57	3.00	5.00	4.00	0.19
Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.

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Indoor operative temp *(°C)*	76	21.82	23.56	22.57	0.45
Relative Humidity (%)	76	48.57	66.06	59.07	5.44
Lux *(lm/m2)*	76	177.40	812.05	380.81	173.61
Metabolic rate *(W/m2)*	24	65.00	90.00	72.92	9.08
Clothing insulation *(clo)*	24	0.57	0.96	0.71	0.16
Gender *(female votes/total votes)*	24	0.00	1.00	0.21	0.42
Outdoor running mean temp *(α = 0.8) (°C)*	4	14.06	15.23	14.80	14.06
Cloud Cover *(okta)*	4	1.00	7.00	5.00	1.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	24	3.00	5.00	3.83	0.42
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	24	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	24	1.00	1.00	1.00	
Thermally comfortable *(4 sensation)*	24	0.00	1.00	0.67	
Moisture comfort vote *(1 out of 7)*	24	4.00	5.00	4.04	0.20

TABLE APP.D.4 Room E1 fall test session descriptive statistics by week

Room D1 Weekly Descriptive Statistics

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	21.75	23.11	22.55	0.38
Relative Humidity (%)	95	38.21	51.09	42.57	4.54
Lux *(lm/m^2)*	95	193.20	1091.90	410.78	225.58
Metabolic rate *(W/m^2)*	48	58.00	110.00	71.40	12.51
Clothing insulation *(clo)*	48	0.57	0.96	0.64	0.09
Gender *(female votes/total votes)*	48	0.00	1.00	0.13	0.33
Outdoor running mean temp *(α = 0.8) (°C)*	5	9.96	12.52	11.34	1.01
Cloud Cover *(okta)*	5	1.00	6.00	3.80	1.72
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	48	1.00	6.00	4.00	0.90
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	48	0.00	1.00	0.79	
Thermally comfortable *(3,4, or 5 sensation)*	48	0.00	1.00	0.92	
Thermally comfortable *(4 sensation)*	48	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	48	2.00	5.00	3.67	0.60

Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	171	23.04	23.81	23.50	0.18
Relative Humidity (%)	171	33.96	52.65	42.97	4.84
Lux *(lm/m^2)*	171	153.70	666.20	425.66	145.25
Metabolic rate *(W/m^2)*	63	65.00	90.00	67.86	7.55
Clothing insulation *(clo)*	63	0.57	0.86	0.62	0.09
Gender *(female votes/total votes)*	63	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	9	7.96	13.76	11.20	1.83
Cloud Cover *(okta)*	9	0.00	7.00	4.13	2.58
Precipitation *(1:snow on ground;2:snowing;3:rain)*	9	0.00	3.00	0.80	1.33
Thermal comfort votes *(1 out of 7)*	63	1.00	6.00	4.10	0.82
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	63	0.00	1.00	0.78	
Thermally comfortable *(3,4, or 5 sensation)*	63	0.00	1.00	0.95	
Thermally comfortable *(4 sensation)*	63	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	63	3.00	6.00	3.76	0.56

Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	114	21.58	22.35	21.87	0.21
Relative Humidity (%)	114	37.07	50.56	44.40	3.97
Lux *(lm/m^2)*	114	153.70	611.00	279.47	118.14
Metabolic rate *(W/m^2)*	59	65.00	110.00	66.95	7.49
Clothing insulation *(clo)*	59	0.57	0.86	0.64	0.10
Gender *(female votes/total votes)*	59	0.00	1.00	0.07	0.26
Outdoor running mean temp *(α = 0.8) (°C)*	6	9.04	10.60	9.77	9.04
Cloud Cover *(okta)*	6	5.00	8.00	6.89	5.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	6	0.00	3.00	1.67	0.00

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Thermal comfort votes *(1 out of 7)*	59	1.00	4.00	3.34	0.73
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	59	0.00	1.0	0.69	
Thermally comfortable *(3,4, or 5 sensation)*	59	0.00	1.00	0.88	
Thermally comfortable *(4 sensation)*	59	0.00	1.00	0.47	
Moisture comfort vote *(1 out of 7)*	59	2.00	5.00	3.75	0.58

TABLE APP.E.1 Room D1 spring test session descriptive statistics by week

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	22.18	23.09	22.54	0.25
Relative Humidity (%)	95	36.56	58.38	47.42	7.44
Lux *(lm/m^2)*	95	145.80	1344.20	635.83	361.55
Metabolic rate *(W/m^2)*	31	65.00	110.00	66.15	7.21
Clothing insulation *(clo)*	31	0.57	0.86	0.62	0.09
Gender *(female votes/total votes)*	31	0.00	1.00	0.10	0.31
Outdoor running mean temp *(α = 0.8) (°C)*	5	14.19	15.29	14.77	0.42
Cloud Cover *(okta)*	5	3.00	8.00	6.40	1.85
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	3.00	1.20	1.47
Thermal comfort votes *(1 out of 7)*	31	2.00	5.00	3.67	0.70
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	31	0.00	1.00	0.79	
Thermally comfortable *(3,4, or 5 sensation)*	31	0.00	1.00	0.95	
Thermally comfortable *(4 sensation)*	31	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	31	3.00	5.00	3.79	0.47
Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	285	22.92	24.32	23.62	0.31
Relative Humidity (%)	285	40.11	69.94	54.31	7.93
Lux *(lm/m^2)*	285	116.80	1328.40	544.59	294.62
Metabolic rate *(W/m^2)*	126	65.00	110.00	66.98	7.93
Clothing insulation *(clo)*	126	0.57	0.86	0.59	0.07
Gender *(female votes/total votes)*	126	0.00	1.00	0.06	0.23
Outdoor running mean temp *(α = 0.8) (°C)*	15	13.55	18.78	16.30	1.54
Cloud Cover *(okta)*	15	0.00	8.00	4.79	2.46
Precipitation *(1:snow on ground;2:snowing;3:rain)*	15	0.00	3.00	0.64	1.23
Thermal comfort votes *(1 out of 7)*	126	1.00	6.00	3.94	0.90
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	126	0.00	1.00	0.79	
Thermally comfortable *(3,4, or 5 sensation)*	126	0.00	1.00	0.90	
Thermally comfortable *(4 sensation)*	126	0.00	1.00	0.56	
Moisture comfort vote *(1 out of 7)*	126	2.00	6.00	3.70	0.61
Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	133	22.32	23.90	23.17	0.44
Relative Humidity (%)	133	51.73	67.01	61.15	4.01
Lux *(lm/m^2)*	133	190.70	1218.00	396.92	324.12
Metabolic rate *(W/m^2)*	41	65.00	110.00	67.80	10.43
Clothing insulation *(clo)*	41	0.40	0.61	0.55	0.05
Gender *(female votes/total votes)*	41	0.00	0.00	0.00	0.00

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Outdoor running mean temp *(α = 0.8) (°C)*	7	16.82	22.18	19.50	16.82
Cloud Cover *(okta)*	7	0.00	5.00	2.11	0.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	7	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	41	3.00	7.00	4.20	1.01
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	41	0.00	1.00	0.83	
Thermally comfortable *(3,4, or 5 sensation)*	41	0.00	1.00	0.93	
Thermally comfortable *(4 sensation)*	41	0.00	1.00	0.44	
Moisture comfort vote *(1 out of 7)*	41	2.00	5.00	3.61	0.67

TABLE APP.E.2 Room D1 Summer Test Session Descriptive Statistics By Week

Week 1: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	95	23.08	24.07	23.56	0.33
Relative Humidity (%)	95	60.30	66.87	63.57	1.90
Lux *(lm/m2)*	95	106.40	1170.70	533.39	362.28
Metabolic rate *(W/m2)*	32	65.00	90.00	68.13	8.40
Clothing insulation *(clo)*	32	0.40	0.61	0.57	0.03
Gender *(female votes/total votes)*	32	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	5	16.48	19.39	17.47	1.09
Cloud Cover *(okta)*	5	0.00	4.00	2.60	1.50
Precipitation *(1:snow on ground;2:snowing;3:rain)*	5	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	32	3.00	7.00	4.38	0.94
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	32	0.00	1.00	0.84	
Thermally comfortable *(3,4, or 5 sensation)*	32	0.00	1.00	0.91	
Thermally comfortable *(4 sensation)*	32	0.00	1.00	0.59	
Moisture comfort vote *(1 out of 7)*	32	2.00	6.00	3.78	0.71
Week 2-3: 25.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	190	22.94	24.07	23.48	0.23
Relative Humidity (%)	190	35.24	52.50	45.35	5.18
Lux *(lm/m2)*	190	138.00	1076.10	333.88	246.63
Metabolic rate *(W/m2)*	60	65.00	90.00	68.42	7.39
Clothing insulation *(clo)*	60	0.57	0.61	0.58	0.02
Gender *(female votes/total votes)*	60	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	10	12.47	17.96	14.48	1.55
Cloud Cover *(okta)*	10	5.00	7.00	6.67	0.62
Precipitation *(1:snow on ground;2:snowing;3:rain)*	10	0.00	3.00	2.75	0.83
Thermal comfort votes *(1 out of 7)*	60	2.00	6.00	4.23	0.62
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	60	0.00	1.00	0.87	
Thermally comfortable *(3,4, or 5 sensation)*	60	0.00	1.00	0.97	
Thermally comfortable *(4 sensation)*	60	0.00	1.00	0.67	
Moisture comfort vote *(1 out of 7)*	60	2.00	4.00	3.68	0.50
Week 4: 22.0°C Setpoint					
Variable	N	Min.	Max.	Mean	Std. Dev.
Indoor operative temp *(°C)*	76	21.96	23.16	22.60	0.35
Relative Humidity (%)	76	41.88	64.91	56.28	5.73
Lux *(lm/m²)*	76	138.00	437.50	249.73	97.66

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Metabolic rate *(W/m²)*	34	65.00	90.00	70.44	10.25
Clothing insulation *(clo)*	34	0.48	0.61	0.58	0.03
Gender *(female votes/total votes)*	34	0.00	0.00	0.00	0.00
Outdoor running mean temp *(α = 0.8) (°C)*	4	14.06	15.23	14.80	14.06
Cloud Cover *(okta)*	4	1.00	7.00	5.00	1.00
Precipitation *(1:snow on ground;2:snowing;3:rain)*	4	0.00	0.00	0.00	0.00
Thermal comfort votes *(1 out of 7)*	34	1.00	5.00	3.71	0.91
Thermally comfortable *(3,4, or 5 sens + 2 pref)*	34	0.00	1.00	0.76	
Thermally comfortable *(3,4, or 5 sensation)*	34	0.00	1.00	0.91	
Thermally comfortable *(4 sensation)*	34	0.00	1.00	0.53	
Moisture comfort vote *(1 out of 7)*	34	2.00	4.00	3.47	0.66

TABLE APP.E.3 Room D1 fall test session descriptive statistics by week

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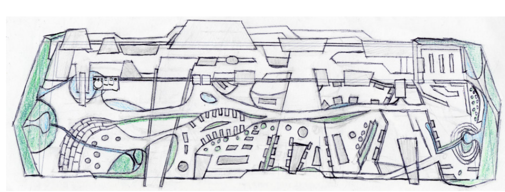
Curriculum vitae

Giancarlo Mangone was born on June 4th, 1985 in Hartford, Connecticut in the United States. He attained a Master of Architecture degree from the University of Virginia in 2009. Prior to commencing his PhD research, Giancarlo worked for a number of architecture firms in North America and China, including Neri + Hu Design Research Office in Shanghai, Fielding Nair International and the government of Puerto Rico, and William McDonough & Partners Architecture in Virginia. In 2009, he began, and continues to run, a research integrated sustainable design and consulting practice, Symbiosis : Sustainable Design + Consulting. His practice has developed and collaborated on innovative, award winning building projects throughout North America, Europe, Africa, and Asia.

Giancarlo Mangone conducted his PhD research within the department of Architectural Engineering + Technology. During the course of his PhD research project, his research was applied to numerous building projects through consultation with firms on projects throughout the world, including the New Lands Commission office building in Accra, Ghana with City Foerster, the Nordic Built Challenge Competition First Prize entry 'Urban Mountain' with Schmidt Hammer Lassen and Transsolar, the Third Place entry to the Moscow Sokolniki park renovation competition with LOLA architects, and several mid-size building projects in Malaysia with Dr. Ken Yeang and his firm, T.R. Hamzah & Yeang Sdn. Bhd.

Giancarlo Mangone is currently an assistant professor of architecture at Carleton University in Ottawa, Canada. He is also the director of the Ecologically Positive Community *[EPC]* design research lab. His design research and pedagogical discourse is focused on investigating the maximum ecological performance potential of buildings and landscapes *[constructed environments]*. This ecological design research approach thereby is concentrated on identifying and developing the greatest possible contributions that the design of buildings can make to mitigating and reversing local and global natural ecosystem degradation. The on-going results of his design research demonstrate that improving the ecological integrity of ecosystems through the design of constructed environments can, at the same time, substantially improve the economic and social performance of constructed environments and local communities, depending on the design solution. This ecological design research is developed in collaboration with engineering, psychology, public policy, ecology, and business academic departments and professional practices, as well as research centers and communities throughout the world. Giancarlo Mangone's interdisciplinary, multi-performance perspective design research approach re-evaluates how people interact with and benefit from constructed environments and ecosystems, generates new symbiotic interrelationships between the ecological, social, and economic performance parameters of constructed environments, questions existing typical design strategies for various building programs, and fosters building scale solutions to help solve society's most dire problems, such as alleviating poverty and habitat destruction, while at the same time, improving the quality and performance of local communities.



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