3 Unpacking density: Translating findings into urban design variables for carbon reduction strategies

Chapter summary

The last chapter identified a range of factors that contribute, individually and in common, to increased GHG emissions per capita. These factors are typically associated with comparatively denser urban forms. This chapter moves beyond density to identify the more particular variables of urban form, and urban design, that can achieve the identified reductions. The chapter examines those factors and their translation into three key urban design variables.

This paper is drawn from "Unpacking Density" (Mehaffy, van den Dobbelsteen and Haas, Nordic Journal of Architectural Research, 2014).

As we saw in the previous chapter, a growing body of research has demonstrated an intriguing correlation between urban density, particularly residential density, and the conservation of energy and other resources, as well as the reduction of greenhouse gas (GHG) emissions (Anderson, Kanaroglou and Miller, 1996; Kenworthy and Laube, 1999; Ewing and Rong, 2008). A number of studies have shown a striking correlation between higher residential density, expressed per capita, and lower energy use and greenhouse gas emissions, also expressed per capita (e.g. Norman, MacLean and Kennedy, 2006). A particularly clear connection has been demonstrated between residential density and transportation energy, beginning with a widely cited study by Newman and Kenworthy (1989).

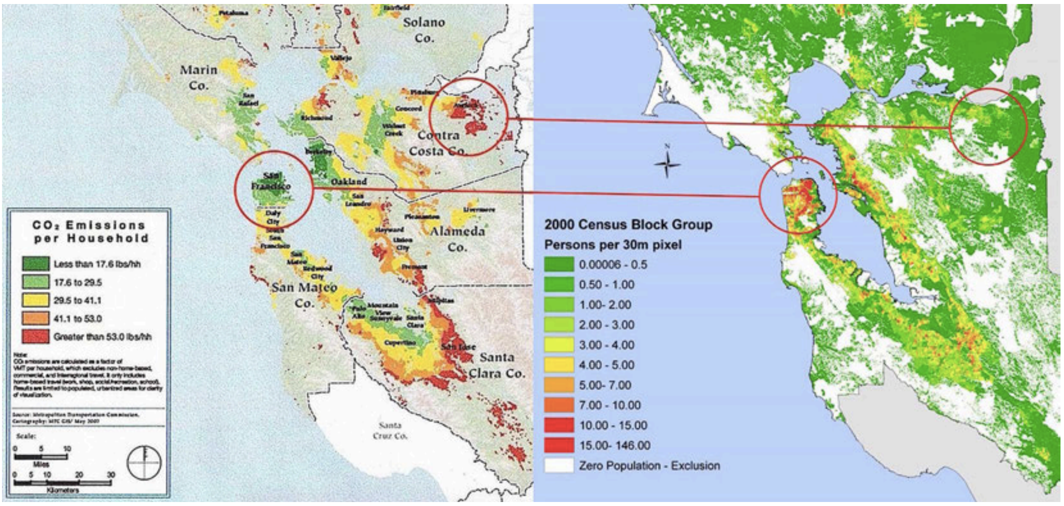

FIGURE 3.1 The striking inverse relationship between density and emissions from transportation is readily visible in this comparison. On the left, a map of the emissions per household from transportation, with green showing lower emissions and red showing higher emissions. On the right, residential density, with dark green showing lower density and red showing higher density. Sources: Left, Metropolitan Transportation Commission, 2007. Right, U.S. Department of the Interior, U.S. Geological Survey.

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But progress has been slower to demonstrate the causal structural components and their interactions at play. As Berg, Granvik and Hedfors (2012) have pointed out, the effects of densification have not been sufficiently evaluated so as to tease out effective planning strategies. Mindali, Raveh and Salomon (2004) begin to look at individual variables of density in the Newman and Kenworthy research, and conclude that it is not density alone that is responsible, but other factors of morphology. While some likely contributions related to scale seem intuitively obvious and relatively well-supported by research (such as the reduction of distances travelled), other less scale-dependent components, such as patterns of distribution, are less clearly understood. Moreover, the pattern of interaction of these factors can be complex and difficult to isolate (Randolph, 2008). In turn this gap in evidence has made it more difficult to exploit these factors so as to establish more effective policy, best practice, and incentive approaches to achieve the goal of more resource-efficient cities (Ewing, et al., 2011).

Thus, there is a compelling need to research the question of the most salient factors, and moreover, how they interact within an urban system, as part of a variable design framework. It is not enough to understand such factors in isolation; what is necessary, as a useful guide to policy and practice, is an essential understanding of their structural dynamics within an interacting system. This is the key research question for the current study.

Specifically, in this chapter we will analyse a framework of three potentially significant factors already identified in research, together with the state of research for their analysis, and we will consider the basis for evaluating their interactions. We will then draw conclusions of implications for urban best practice as well as further research needed.

First, we will examine the structural distribution of uses and destinations – a factor we will refer to, in short, as the *web of destinations* – and assess what is known about the importance of characteristic patterns of distribution for resource efficiency.

Second, we will examine the provision of viable pedestrian-based multi-modal pathways – what we will refer to as the *web of transportation* – and the characteristics that they are known to require.

Third, least understood but perhaps most intriguing, we will examine the effects of what we term the *neighbourhood network* that appear to arise from the dynamics of network structures such as pedestrian pathways.

Lastly we will examine these factors as an interactive group, so that we can begin to understand the structural dynamics by which they interact. By varying these structural factors in relation to one another, we may thus be in a position to achieve significant reductions of greenhouse gas emissions as well as other benefits.

It is important to state at the outset that such a framework is only the beginning of a longer iterative process of evaluation, refinement and greater efficacy. But it is in the nature of complex systems, including cities and city design, that relatively simple and robust decision-making models, informed by research, and improved by iterative cycles of empirical application, evaluation and adjustment, are capable of achieving remarkable and promising levels of effectiveness (Dawes, 1979).

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§ 3.1 Implications of Previous Research

As noted, previous literature has already identified a significant number of factors that play a role in the apparent benefits of compact urban environments. At this point it is fair to say, however, that as individual components they have not been able to account for the magnitude of empirically observed effects upon conservation of energy and resources, or reduction of greenhouse gas emissions per person.

Indeed, some investigators have suggested that, while compact urban environments can produce beneficial results, the actual magnitude of benefits may be so marginal that they do not rise to the level of a useful strategy for policy or practice. In a notable example, the US National Research Council (2009) attracted significant attention in its conservative finding on the impact of greenhouse gas emissions as a result of densification. However, Ewing, et al. (2011) noted that the study also made quite conservative assumptions which were, at best, not warranted by the evidence, and may have reflected an academic bias. In addition, the study looked only at greenhouse gas emissions reductions from private vehicle travel, which is only one of a number of factors. By contrast, Ewing, et al. argued that the evidence does suggest that a densification strategy could achieve significant results, but more work is needed to tease out the factors.

Other investigators have raised notable counter-arguments to the specific claims for the benefits of compact urban environments altogether. Neuman (2005) is typical of those who have pointed out that, whatever the benefits may be from densification, there are negative impacts as well that are often ignored, and that may well offset the benefits. Moreover, Neuman and others challenge what they argue is an implicit conception of cities wholly in terms of their form, rather than in terms of their processes.

Rebutting the work of Neuman, however, Hillier (2009) and other researchers using the framework of "Space Syntax" have demonstrated that the morphology of spatial networks (including, in part, their density) does have important implications for resource use and greenhouse gas emissions.

Furthermore, the fact that densification may have negative impacts cannot by itself be a disqualification for this strategy, since almost any design strategy is likely to result in a mix of negative and positive impacts. It is precisely the role of a study such as this one to provide useful predictions of the outcomes of such strategies. From that point, informed practitioners have the responsibility to apply this knowledge to achieve the best outcome in a given context, as defined by the stakeholders and verified through empirical observation and refinement.

The contrarian research may therefore suffer from a failure to observe "the forest for the trees". Ample research does show large variations in magnitude of greenhouse gas emissions, at least associated with – whether or not yet proven to be caused by – variations in urban form. For example, as documented by the World Resources Institute (2009) and others, the magnitude of observed differences in greenhouse gases between cities and their country averages in different countries can be readily observed to be as much as six-fold – an enormous magnitude indeed. It is, at the very least, difficult to account for this magnitude, apart from very evident differences in urban form. It follows that an effective strategy to achieve changes in urban form – while recognizing the need to balance other factors and their effects – remains a promising subject of investigation.

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It also follows that the challenge remains to identify the factors that have been shown by previous research to have substantial impacts, and to explore how aggregations and interactions of such factors may indeed help to explain – and to achieve – significant reductions.

Among the most thoroughly investigated factors to date are:

Jobs-housing balance. The work of Cervero and Duncan (2006) is typical of studies that showed that this factor is particularly important, and more important than availability of retail and consumer facilities.

Mix of uses. Brown, Southworth and Stovall (2005) pointed out that a variety of uses is also important, and related to the distribution of destinations discussed further below. Dobbelsteen and Wilde (2004) demonstrated that a mix of multiple uses in space promotes more efficient land use, particularly when combined with intensification (i.e. higher density in both residential and non-residential uses).

Multiple uses over time. Dobbelsteen and Wilde (2004) also demonstrated that spaces that can be used in multiple ways also promotes more efficient land use, since a single facility can be used to accommodate multiple activities (e.g. a school used for evening community meetings).

Viable multi-modal transportation. Research by Bovy and Hoogendoorn-Lanser (2005) and others has shown that, other things equal, a well-coordinated multi-modal system including convenient public transport supports lower-energy transport modes. See also Hydro-Québec (2005).

Role of infrastructure embodied and operating energy, and transmission losses. The operating energy of pumping and lighting systems can be significant, as well as the energy and resources lost in transmission. These effects are generally sensitive to compactness of form (Rong, 2006; Hydro-Québec, 2005).

Ability to exploit district-scale energy efficiency and demand management. Many energy systems are able to produce significant efficiencies through co-generation and waste heat use, as well as through district-scale management of energy demand (Rosen, Le and Dincer, 2005; Marshall, 2008).

Behavioural and economic factors. It is reasonably well established that compact environments tend to be associated with smaller homes and more resource-efficient behaviours, relative to others (Liu, et al., 2003; Ewing and Rong, 2008). However, while the association has been well-documented, the causal mechanism or mechanisms (such as, perhaps, the "choice architecture" of different environments, as discussed further in Chapter 4) have not been. Nonetheless, the magnitude of the embodied energy and resources consumed as a result of these factors is large (Lenzen, Wood and Foran, 2008).

Meta-analyses and multi-disciplinary analyses have also been done for these factors, notably by Clifton, Ewing and Knaap (2008). The authors concluded that there are a number of advantages to urban form that is mixed and compact, but there is also a need for more standardisation in research protocols. Moreover there is a need for normative principles and policies to be crafted at multiple scales, and carefully designed to address the disparate issues that arise at each scale. This is a key sub-goal of the research herein.

§ 3.2 Identifying salient urban design factors and their interactions

For urban designers, there is a particular need to translate the factors identified to date into useful urban design variables that can be used to analyse and model options. One key problem with the factors identified to date in the literature is that they are generally considered in isolation, and it is difficult to understand, in a useful way for urban designers, how they interact in practice. This results in the familiar problem of proliferation of unintended consequences: one variable may be optimised while others are neglected, often reducing or erasing the benefit. For example, in what is known as Jevon's Paradox, increasing the efficiency of devices reduces their cost of operation, which tends to increase demand, thus reducing or erasing the gain from efficiency.

Thus it is of central importance to identify the salient factors that interact, so as to understand them usefully within a system of design elements, while accurately modelling the complexity of the system. In a sense, we want the optimal balance between simplicity and complexity, such that our models are simple enough to operate in a comprehensible way, but complex enough to model actual urban phenomena in a sufficiently accurate way. This is of course the ultimate challenge of all modelling.

Here we propose a morphological framework of just three factors, which aggregate and integrate the factors above in a way that they can be more easily understood as individual factors, and in their patterns of interaction with one another. The details of these interactions are discussed later in the paper.

It should also be noted that in any urban design process, many other criteria must be considered, including particular aspects of the local context which vary greatly. There is all the more reason, then, to maintain a manageable number of factors, so that any other necessary factors can also be considered. In this way, individual criteria (including GHG emissions) are not considered in isolation, but within a comprehensible and comprehensive model that can address other factors.

The three aggregated factors mentioned in the outset of this chapter, and discussed in more detail below, are:

Web of destinations: This factor combines jobs-housing balance, mix of uses, and multiple uses over time. It describes (as far as research to date makes known) the optimal distribution of destinations so as to minimize travel and maximize efficient use of resources. It is intended to be useful in identifying patterns of optimal spacing that urban designers may use in preparing design scenarios for comparison and analysis.

Web of transportation: This factor combines viable multi-modal transportation, embodied and operating infrastructure energy, and behavioural and economic factors. It describes (as far as research to date makes known) the optimal integration of modes of transportation, beginning with pedestrian travel and integrating other modes most efficiently into a viable multi-modal network. Again, this factor is intended to be useful in identifying patterns of optimal integration of multi-modal transportation systems, in a way that urban designers could use in preparing design scenarios.

Neighbourhood Network: This factor combines district-scale energy, infrastructure embodied and operating energy, and behavioural and economic factors. It describes (as far as research to date makes known) the optimal form of a neighbourhood to maximise so-called network effects, and minimise resource use and GHG emissions. This factor is intended to be useful in optimising the overall structure of a neighbourhood both internally and in relation to adjacent neighbourhoods, as part of a comparative analysis of design scenarios.

These are certainly not the only factors that one might identify in urban design scenario-modelling. Other factors include building size and orientation, unit types and sizes, building-scale technologies, and many others. But our research has convinced us that these factors are most in need of clarification, and subsequent integration into a useful urban design scenario-modelling approach. They may also serve as the first elements of a wider modelling approach, based in part on the work described herein.

Below we consider each of the three factors in more detail.

§ 3.3 Web of Destinations: The role of efficient distribution of destinations

A growing body of research confirms the logical supposition that certain distributions of regular travel destinations (such as work, retail, services, recreation and civic uses) will result in more energy and resource consumption per capita than others (Handy, 1996; Clifton, Ewing and Knaap, 2008). For example, the highly dispersed destinations of a rural environment will, other things held equal, require an increase of energy for transportation, relative to a dense urban environment. But a similar requirement will hold for inefficient distribution of urban destinations, such as highly centralized retail cores.

Much of the understanding of efficient patterns of distribution has come from network science, graph theory and Space Syntax, notably the work of Hillier (2007), Hillier and Hanson (1984) and others who have followed on that work. Marcus (2007) demonstrated how Space Syntax helps to account for the social performativity of a given spatial distribution pattern. Ståhle, Marcus and Karlström (2005) explored the geographic accessibility provided by a range of distribution patterns under analysis by Space Syntax.

Additional evidence for the effects of various distribution patterns comes from research on the distribution of destinations as a result of so-called “self-organizing” processes that tend to achieve efficiencies (such as economic processes that seek the lowest available cost).

In the field of spatial econometrics, or the economic effects of geographic pattern, there has been extensive work on the spatial distribution of land uses and their consequences. Irwin and Bockstael (2002) described a process whereby agents interact with each other and with externalities to produce characteristic and economically efficient urban forms, including the distribution of destinations. It is important to note that the forms may be efficient from the point of view of economic interactions, but not necessarily with regard to resource consumption and other so-called “externalities”. Indeed, this disparity between efficient economic processes and inefficient externalities like resource consumption seems to account well for the phenomenon of urban sprawl.

Similarly, White and Engelen (1993) applied a model of cellular automata (agents following rule-based interactions) to describe a self-organising distribution process, resulting in a characteristic “fractal” pattern of uses (i.e. patterns that are self-similar at larger and smaller scales). Similar work by Batty (2001) shows how the self-organising processes of urban settlement create fractal distributions that follow a power law (that is, they follow an exponential distribution curve with a few large elements at one end, and many small ones at the other).

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Hillier (1997) proposed a related theory that human movement itself shapes a fractal pattern of destinations over time, which continue to self-organize into a more efficient "movement economy". For Hillier, one of the most problematic results of modern planning and zoning models is that they greatly inhibit this self-organizing pattern.

An important implication is that fixing the destinations by planning directive may be far less efficient than developing a process whereby the destinations can be allowed to self-organize. But as Hillier notes, in order for this to occur, the initial movement network must also be provided in an efficient pattern, which he describes as a deformed grid (Hillier, 1999a).

FIGURE 3.2 Sherford, a new community in the UK designed by Paul Murrain and other associates, using Space Syntax analysis over several iterations of design refinement. The blue lines are principal streets, the smaller red circles are neighbourhood centres, and the larger dotted grey circles are their pedestrian catchment areas. The analytical technique of Space Syntax guides a more efficient synthesis of urban form. Source: Paul Murrain Ltd. and The Prince's Foundation for Building Community.

For city planners and designers, this creates a conundrum: How do they know how to establish the characteristics of such a movement network? Hillier's Space Syntax analytical method (2007) proposes a methodology. The analysis process allows development and testing of alternate scenarios. The successful scenario is one that is most likely to accommodate an efficient distribution. Once the street network is constructed, it is not necessary to assugn the uses through zoning or other top-down mechanisms. An efficient web-like pattern will spontaneously develop – the same process of urban self-organization that has occurred in cities throuhout history.

A relatively mature body of work has demonstrated how these web-like patterns function to provide a range of benefits, including resource efficiency and GHG reduction. We previously mentioned Hillier's work in Space Syntax applied to resource efficiency and sustainability (2009). Marcus and Colding (2011) also used network concepts to describe a "*spatial morphology of urban social-ecological systems*."

These tools of network analysis allow the development of efficient networks, by serving as tools to iteratively explore the likely outcomes of design scenarios. In so doing they do not seek to replace self-organization, but rather to serve as a facilitator of it. In this sense the job of planners and urban designers is not so much to allocate the elements of urban structure efficiently, but to provide the framework to facilitate their efficient growth by other actors.

§ 3.4 Web of Transportation: The role of viable pedestrian-based multi-modal pathways

As noted previously, investigators such as Bovy and Hoogendoorn-Lanser (2005) have demonstrated that multi-modal transport systems play an evident role in resource-efficiency and GHG emissions reductions. But there is a deeper question of what morphology such systems require for optimum function. To tease this out, we can begin by assessing the specific role of pedestrian pathways within the larger multi-modal network.

It can readily be seen that this role is fundamental, since almost every trip by any mode begins and ends with a pedestrian trip. If users are not able to walk to transit stops, or to convenient parking for vehicles or bicycles, then they are not likely to find that mode of transport viable. Moreover, the ability to use more resource-efficient modes such as walking and biking may in itself result in greater resource efficiency overall. Thus the question of the functionality of pedestrian-based transport pathways (also accommodating bicycles and perhaps other modes) is an important one for research.

Significant work has been done on the characteristics of well-used pedestrian-based pathways. A growing body of research demonstrates a strong correlation between walkable neighbourhoods and such factors as high intersection density and short blocks, and diversity of close-by destinations (e.g. Leslie, et al., 2005; Berrigan, Pickle and Dill, 2010).

Investigators such as Law, Chiaradia and Schwander (2012) and Samaniego and Moses (2008) have explored the web-like structure of multi-modal pathways from the perspective of graph theory. As with other findings from network science, the pattern of interconnections of pathways is critical, as is the relationship between paths and nodes. As with related work in Space Syntax, the findings establish a useful set of criteria for assessing and modelling complex urban design options.

Another important component is the aesthetic character of the walking environment. Cerin, et al. (2006) showed that the presence of vegetation is associated with greater walking. Other investigators found similar results for both walking and biking (Saelens, Sallis and Frank, 2003, Wahlgren and Schantz, 2012)

Related findings come from environmental psychology. A classic study by Ulrich (1984) showed that a view of natural scenery from a window could produce a measurable improvement in patient outcomes. Follow-up studies established a number of remarkable effects from natural, "biophilic" characteristics such as vegetation, water and natural geographic features. The design of healthcare facilities has exploited these insights through what is known as "therapeutic horticulture" (see e.g. Sempik, Aldridge and Becker, 2003).

There is evidence that the benefits of these biophilic characteristics extend well beyond the patient healthcare context. Parsons, et al. (1998) described the role of vegetation in reducing stress among urban commuters. Nikolopoulou and Steemers (2003) reported that the experience of thermal comfort in urban areas varied not just according to actual temperature, but also according to experiential factors such as presence of vegetation and ability to control the environment. Other research has shown that the experience of other people and animals, even if only sensed behind a window or wall, has restorative effects (Kaplan, 1995).

Salingaros (2010) argued that such biophilic characteristics are also generated by buildings themselves, and specifically by their fractal, ornamental and other geometric characteristics. It is not just adding trees and shrubbery around buildings that is important, but creating the geometric characteristics of natural environments that humans find naturally pleasing and restorative: complexity, variety, layering, “prospect and refuge”, symmetry, grouping, and other “natural” characteristics.

At the level of a streetscape, these geometric characteristics create interest and appeal for pedestrians. They maintain a range of scales to view at different distances, and they entice pedestrians to continue an enjoyable walking trip. They present an endlessly changing vista, with layers of experience containing other people, animals, vegetation, sunlight, water and other appealing factors.

All of these findings are reinforced by research into actual increases in walking and biking activities, and the factors demonstrated to be most closely associated with those increases (e.g. Saelens, Sallis and Frank, 2003).

§ 3.5 Neighbourhood Network: The role of urban “network effects” as they affect behaviour, demand and resource consumption

An intriguing area of investigation is the role of particular connective patterns within the urban system, in relation to others – a domain in mathematics known as graph theory, also commonly known as network theory (Borgatti, et al., 2009). This topic is clearly important for the evident reason that some patterns of connections make possible some forms of exchange of resources, while other patterns do not.

In biological systems, network theory helps to account for the way that certain flows of biological products promote “metabolic” efficiencies, that is, efficient use of chemical products to promote the growth of more complex structures (Stelling, et al., 2002). These processes are highly sensitive to the connective patterns of the flows, and network theory – specifically, “metabolic network modelling” – helps to understand how they inter-connect, and how they achieve their efficiencies. For example, Ko, Bentley and Weigand (2004) describe “*an integrated metabolic modelling approach to describe the energy efficiency of Escherichia coli fermentations*”. As they note, this network model helps to explain efficiencies that are beneficial in industrial fermentations.

A strong corollary can be found in economics, where networks of interactions can promote “spillovers”, or interactive exchanges of knowledge and other resources. This topic has been the subject of considerable research within economics and economic geography (Glaeser, 2009; Desrochers and

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Leppälä, 2011). The question has begun to be explored how this network "spillover effect" might also apply to urban resource efficiencies as well (Mehaffy, 2011).

Other investigators have explored the role of network structure within urban systems, and their implications for movement and interaction (e.g. Cullen and Godson, 1975). The aforementioned work on Space Syntax by Hillier et al. relies explicitly on network theory concepts such as centrality (Hillier, 1999b). Batty (2008) calls for an integrated theory of how cities evolve, linking urban economics and transportation behaviour to developments in network science and related fields, and he gives an outline of what is known, while pointing out the urgent need for more work.

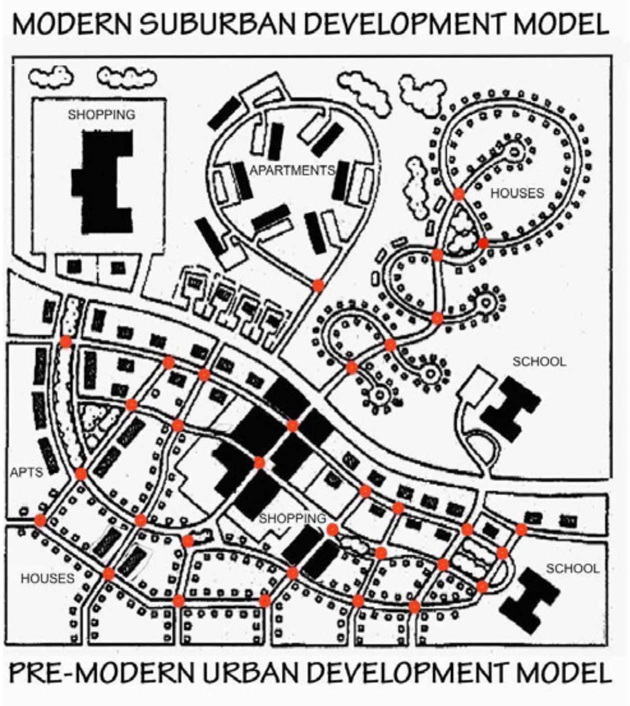

FIGURE 3.3 The street system at the top of this diagram follows a "mathematical tree" structure – few if any of the "branches" inter-connect. The lower structure is a "mathematical lattice", with many more redundant inter-connections, shown in red. It can readily be seen that average trips between any two random destinations in the "tree" form will be longer than average trips in the "lattice" form. It is notable that the ingredients are the same in the top and the bottom, but only the pattern of connectivity varies. Source: University of Miami (2013).

Hillier is also careful to note that cognitive effects can play a role that overrides mere network effects alone (Hillier and Iida, 2005). Salingaros (2005) also makes extensive use of neuroscience as well as network theory to understand the dynamics of urban interactions. It is not only our movements that are connected in patterns of networks, but our spatial experiences. Such work points the way to a kind of "place network theory" that integrates physical, cognitive and behavioural factors.

More specifically, how can we account for the relation of network theory to resource efficiency? One simple example begins to suggest an avenue for exploration. In the morphology of street systems, it is possible to have alternate designs with very different degrees of inter-connection. At one extreme is what is known as a "mathematical tree" – a branching hierarchy with very few inter-connections (Figure 3, top). An alternative model is what is known as a "lattice" – a structure that has many interconnections (Figure 3, bottom).

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It can readily be seen that average trips between any two random destinations in the "tree" form will be longer than average trips in the "lattice" form. It will be more likely that a "shortcut" is available in the lattice, relative to the tree structure.

Common urban design models of the 20th Century made extensive use of the "tree" form as a way of enhancing vehicular mobility (Mehaffy, Porta and Romice, 2014). Because it was assumed that most trips would be made with vehicles powered by relatively cheap energy, only secondary consideration was given to the characteristics of pathways for other modes, or their degree of inter-connection. Such morphological differences have had profound consequences on the pattern of mobility and resource efficiency of these urban areas (Pushkar, Hollingworth and Miller, 2000).

Moreover, it is not just transportation networks that are affected by network relationships. In a highly influential paper, Alexander (1965) argued that the tree-like relationships introduced by modern planning models constrain many other aspects of city life. Alexander pointed out that historical cities tended to have the characteristics of a "semi-lattice", with many inter-connected relationships. These inter-connected relationships extended to many different components of the urban environment.

Alexander used this mathematical argument to mount a powerful critique of existing planning models based on hierarchical "tree" organizations. "*The enormity of this restriction is difficult to grasp*", he noted, "*It is a little as though the members of a family were not free to make friends outside the family, except when the family as a whole made a friendship*" (Ibid., p. 58).

Alexander went on to make a crucial structural conclusion: "*It must be emphasized, lest the orderly mind shrink in horror from anything that is not clearly articulated and categorized in tree form, that the idea of overlap, ambiguity, multiplicity of aspect and the semi-lattice are not less orderly than the rigid tree, but more so. They represent a thicker, tougher, more subtle and more complex view of structure.*" (Ibid., p. 58)

Alexander's words foreshadowed the later work on metabolic network modelling as well as the related work on urban economies discussed previously. But the question remains for further investigation: Apart from simple density, how does the structure of such network relationships actually produce resource efficiencies, and related benefits such as greenhouse gas emissions reductions?

One such benefit has already been suggested: The redundancy of connective relationships allows optimization of more efficient pathways. As we saw, this holds true for transportation networks, but it seems plausible that the same would hold true for other kinds of interconnected, redundant relationships. For example, redundant relationships between a user and that user's available destination types would allow a more efficient generation of combined trips, across an average of randomized lists of destinations, if those destinations were inter-connected into a semi-lattice structure.

Another apparent benefit is that, at the scale of a pedestrian network, a user has a greater choice to explore more efficient activities, and a greater incentive to do so. Because of the personal energy investment in walking, there is a greater incentive to combine trips, and to find shorter paths. An inter-connected pathway provides those shorter paths and combined trips. By contrast, a vehicle-based trip to more distant destinations over a more centralized, "dendritic" street system is likely to promote even less efficient travel behaviour.

It is at this point that, as Hillier and others have noted, we must recognize the role of cognitive factors, beyond a mere structural configuration. What a person experiences within a pedestrian network will

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be different from what a person in a vehicle will experience. The structure of choices before them – what behavioural economists refer to as the “choice architecture” – will be notably different. There is evidence that this difference will have an impact on the form and degree of consumption, with implications for resource use and greenhouse gas emissions (Johnson, et al., 2012).

It is plausible to hypothesize that a compact, walkable urban network will, for the reasons discussed, tend to offer a more inherently efficient choice architecture than a dendritic, vehicle-dependent system, which will tend to promote a much higher level of consumption of fuels and other consumer products. The empirical evidence of consumer behaviour tends to confirm this hypothesis, although this subject is in need of much more detailed investigation.

§ 3.6 Modelling the interaction of the three urban design factors

It can readily be seen that the previous three factors do not function in isolation from one another, but work together within an urban system. Clearly the presence of pedestrian-based multi-modal pathways within a neighbourhood will inter-depend with the distribution of its destinations, and in turn both of these factors will inter-depend with the structure of their connective network and its interactive effects. For accurate and effective guidance of policy and best practice, these dynamics must be identified and understood. The goal of research, in that light, is not to tease out these factors merely to treat them in isolation, but to better see, and model, their useful combinations into larger models of planning and policy. Though much more work will be required to fully establish the dynamic relationships involved, we can begin to map them here (Table 3.1).

For example, we can ask what happens when there is a viable multi-modal pathway, but the distribution of destinations is uneven and inefficient. It seems logical that the multi-modal pathways will then be under-utilized, and modes that are able to convey passengers more quickly over longer distances (with higher consumption of resources) will predominate. For automobiles conveying one or two passengers, this implies an even higher level of resource consumption.

In fact we do find that in a comparison between cities with concentrations of destinations and those with more dispersed destinations, even when both have multi-modal pathways, the rates of consumption are notably higher in the former (Pushkar, Hollingworth and Miller, 2000; Cervero and Duncan, 2006). In this way we can confirm and refine such a framework, drawing on additional research as it becomes available.

Similarly, it seems very likely that when there is no viable multi-modal pathway, the network effects on consumer interaction and behaviour will be affected. Bettencourt (2013) finds this to be the case, and notes that cities that “*remain only incipiently connected will typically under-perform better mixing cities in terms of their social outputs*”.

In those cities where increased automobile travel is a widely available alternative, it seems very likely that the result will be more travel over longer distances, and a tendency to consume “drive-through” “fast-food” product offerings that are far less resource-efficient – for example, processed foods, meat products, products with high amounts of disposable packaging waste, and so on.

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Indeed, research does show a correspondence between travel distance and increasing rates of consumption (for example, Carlsson-Kanyama and Linden, 1999). This tendency is also described by research in so-called "choice architecture", described further in Chapter 4. There is evidence to suggest that the structure of choices visible to a consumer – such as the selction of drive-through food products for an automobile driver – will greatly influence consumption patterns (Lockton, Harrison and Stanton, 2009).

Lastly, it seems that cities with an inefficient distribution of destinations will also suffer from a diminution of the otherwise beneficial network effects on behaviour and demand. The research does tend to bear this out. Bettencourt (2012) points out that a city is a "social reactor" and that socioeconomic outputs (such as creation of new enterprises) are proportional to local social interactions within public spaces. This network phenomenon (first suggested by Jacobs (1961), and further established by Glaeser (2009) and others) presupposes an essential level of connectivity and power-law distribution.

With three factors, there are seven possible combinations of factors, depending on which of the three factors is present. (A, B, C, AB, BC, AC, ABC). It is then possible to map out what are the likely outcomes of combinations of the factors when combined optimally. Table 3.1 provides a summary of how such a framework could offer increasingly accurate predictions of reductions, which are shown only as initial plausible approximations at this time.

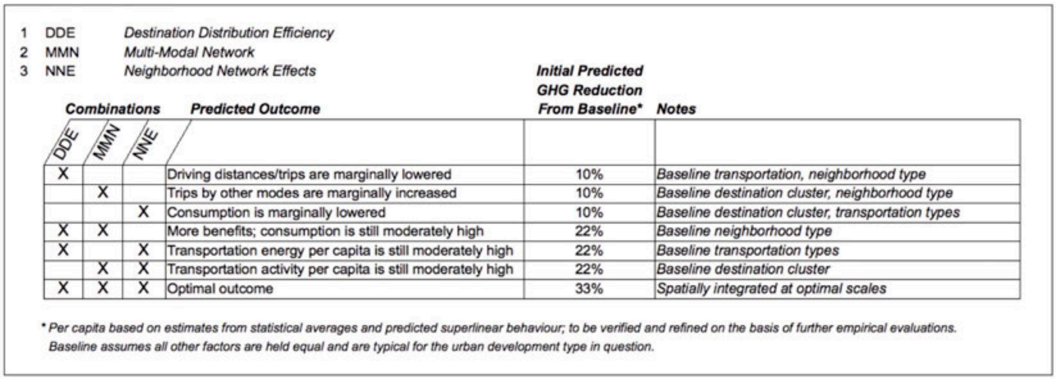
Just as removing one of the three factors reduces the benefits gained by the others, so too, adding one of the factors produces greater benefits. But there is evidence that such benefits are not linear, that is, not a function of simple addition (therefore not producing a "linear" graph, or a straight line on a graph). They often produce so-called "super-linear" results, which are greater than the sum of their individual effects. This makes intuitive sense when one understands that the elements of such a system reinforce each other, and produce synergistic and compounding effects.

The magnitude of such a superlinear result within urban systems is known to vary according to many factors, including scale (Batty, 2008; Bettencourt, 2013). It is not uncommon to see a ratio of about 1:1.1, or about ten percent more benefit than the addition of the individual benefits alone would be expected to produce.

Thus an initial reduction of, say, 10% per factor, might well yield more than 20% for two factors combined, or 30% for three factors combined. In this example, following the ratio of 1:1.1, we show a plausible estimated super-linear result of 22% for two factors, and 33% for three.

Greater accuracy will require further research and empirical refinement, as well as adjustment for local conditions. But as we noted previously, such a relatively simple framework, able to be iteratively and empirically improved, can have robust effectiveness in modelling decision-making under surprisingly complex conditions, as Dawes (1979) and other authors have shown.

We stress that the status of the research in this area is immature, and more research is needed to fill in the picture and establish more reliably predictive patterns of interaction. Even so, we trust that this first step clarifies the nature and importance of the type of model indicated, and thereby makes substantial progress in answering the key research question posed in this study.



1 DDE *Destination Distribution Efficiency*
2 MMN *Multi-Modal Network*
3 NNE *Neighborhood Network Effects*

DDE	MMN	NNE	Predicted Outcome	Initial Predicted GHG Reduction From Baseline*	Notes
X			Driving distances/trips are marginally lowered	10%	*Baseline transportation, neighborhood type*
	X		Trips by other modes are marginally increased	10%	*Baseline destination cluster, neighborhood type*
		X	Consumption is marginally lowered	10%	*Baseline destination cluster, transportation types*
X	X		More benefits; consumption is still moderately high	22%	*Baseline neighborhood type*
X		X	Transportation energy per capita is still moderately high	22%	*Baseline transportation types*
	X	X	Transportation activity per capita is still moderately high	22%	*Baseline destination cluster*
X	X	X	Optimal outcome	33%	*Spatially integrated at optimal scales*

** Per capita based on estimates from statistical averages and predicted superlinear behaviour; to be verified and refined on the basis of further empirical evaluations. Baseline assumes all other factors are held equal and are typical for the urban development type in question.*

TABLE 3.1 Simplified model for the interaction of the factors and their results.

§ 3.7 Conclusion

The mitigation of greenhouse gas emissions from urban systems presents a profoundly complex problem that can, it now appears, only be solved with effective new methods, bridging the gaps between disciplinary specializations, and between research and practice. Those methods must be simple enough to be useful in practice, but robust enough to be empirically effective. They must have the capability to iterate, refine and "learn" within a complex and uncertain environment.

But we would be unwise to apply such methods in isolation from other current and age-old criteria for good city-making. A "compact city" – or any other single factor – is not a guarantee of benefits, and, depending on the relation of other factors, it could well be negative. Those who pursue abstract planning goals in isolation – including greenhouse gas reduction – should certainly take note that many factors must be successfully integrated to produce a well-performing urban environment of any sort. As Neuman (2005) and others note, for example, there is the fundamental but elusive factor of "liveability": It bears remembering that the theoretically best-performing urban environment will not perform well in practice if people simply do not choose to live there, or do not thrive there.

The challenge, then, is to provide pragmatically useful modelling tools and strategies to practitioners, policymakers and citizenry, which can predict reasonably well the actually observed structural dynamics of interacting urban design factors such as those presented here. Such tools need not – and cannot – be perfectly precise. However, they must have the capability to adapt and evolve in response to empirical results and local variations. The framework developed here is meant as a step toward that important goal.

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