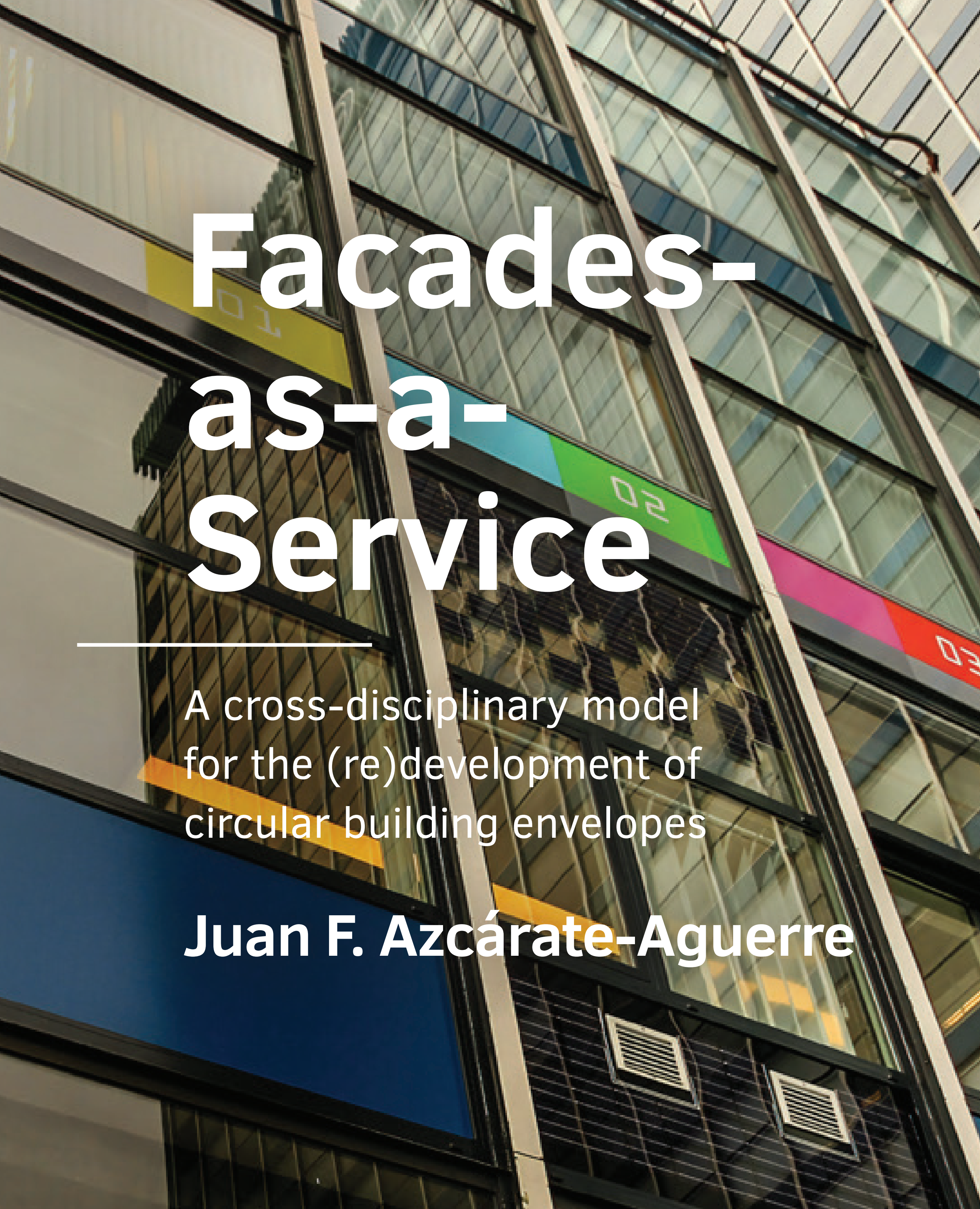

Facades-as-a-Service

A cross-disciplinary model for the (re)development of circular building envelopes

Juan F. Azcárate-Aguerre

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Facades-as-a-Service

A cross-disciplinary model for the (re)development of circular building envelopes

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Tuesday, 20 June 2023 at 15:00 o'clock

by

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To Tillmann

An exceptional mentor, an even better friend.
You are most terribly missed.

Preface

This thesis is the conclusion of over 8 years of work - albeit with widely varying degrees of focus - starting with my MSc project at TU Delft in 2014. During this time, at least in the real estate and construction sectors, the “Circular Economy” term has gone from a relatively obscure topic theorised by academics and promoted by the Ellen MacArthur foundation, to an increasingly mainstream topic favoured by branding and marketing campaigns across many industries. The knowledge and public awareness gaps vary massively between regions, but it is quickly becoming a household term in the general public’s vocabulary.

Personally, during roughly these same last 8 years, I founded and developed – with the help of many valuable individuals – a residential and commercial real estate investment and redevelopment firm. This firm and the scale of its projects grew much faster and larger than any of my original wildest dreams. It also provided thrills and headaches the likes of which I do not feel the need to experience again. This combined career in academy and practice allowed me to pursue and combine two of my strongest professional interests: the role of technology in sustainable construction, and the real-world economics of the construction and real estate sectors. It was also hugely influential to this thesis, as it provided a level of perspective on the concrete challenges faced by individual decision-makers that I would have never been able to achieve if my mind had remained fully immersed solely in the world of scientific research and theory.

Façades-as-a-Service is first and foremost a thesis about decision-making in construction projects; the cultural, business, and economic inertia which largely constrain and define these decisions; and the value extracted from - and responsibilities distributed by - this systemic inertia. The system we live in sets the boundary conditions which determine most of our choices, often without us as individual actors in the system being even aware of it. The Circular Economy is a massive shift affecting many of the fundamental concepts behind this existing system and the practices it promotes, defines, and hinders. Rather than trying to force a circular model into a linear mould, it is crucial to first understand which aspects of our current system are not conductive or may even be detrimental to this evolution. We must critically evaluate whether these systemic parameters are leading to the changing outcomes and strategic priorities our societies require and whether – in our day-to-day work – we are even asking and being asked the right questions. I hope this work will provide one small steppingstone along this path.

Acknowledgements

As I look back on the 8+ years of work behind this PhD thesis, my first question is why? Was it really necessary? Shortly behind this thought comes the realisation that it was indeed necessary for me. That regardless of whether I managed to touch on all the topics I wanted to touch on, at the level of detail I wanted to develop them (which I surely did not) it is still valuable and relevant to make this information and knowledge available.

My promotors, Tillmann and Alexandra, deserve the biggest share of the credit for believing in this topic, and for putting their effort, energy and enthusiasm into making it happen. All the thought, pilot projects, industrial collaborations, and publications behind this thesis are the direct result of their motivation and their passion. I could not be more grateful to them.

I am also grateful to Thaleia - my co-promotor, daily supervisor, and colleague – for reminding me often (but not too often) that regardless of whatever else was going on in my professional life I should still find the time to structure this thesis and slowly push the PhD rock up the hill.

I am massively grateful to Martijn Veerman, who has acted as the physical embodiment of the Dutch façade industry in this research and thesis. Martijn has been dedicating his life to this topic since even before I did, and he will likely continue to do so long after I move on to other things. I wish him all the best and know that if anyone can solve all the remaining challenges and make this work it will be him.

I deeply appreciate the work done by many individuals and organisations in practice: EIT Climate-KIC, TU Delft's Campus Real Estate (TUD CRE), the Dutch Metal Façade Industry Branch Organisation (VMRG), Alkondor Hengelo, and the countless other fabrication companies, product and system suppliers, legal, banking, and fiscal experts, and so many others who played a role in the research and its pilot projects. Also, to everyone who was involved in these projects behind the institutional curtains, but who I never had the chance to meet. I would not have been able to research a topic in which industry was not actively involved, and in which real and large-scale pilot projects did not get built.

Lastly, I thank all my academic co-authors, who kept reminding me over the years that this or that paper was not yet published, and that it just needed one last little push (whether or not this was true). The international, practical, and multi-disciplinary nature of this research was a big part of what kept me motivated and interested.

On a more personal level, I am grateful to my father, who taught me from an early age a large part of what I know about finance, business, and the “real-world”, and taught me that scientific research and industry must not (and often should not) pursue different paths. To my mother, who thought me most of the rest of what I know about finance, business and the “real-world”, and who taught me that real estate investment is not – despite public opinion to the contrary – a source of *passive* income, but an ongoing social and technical responsibility requiring ones’ constant attention.

To all my friends and colleagues, many of whom became doctors before I did, who learnt not to ask too frequently how my PhD was going, and who were satisfied with a brief cutting reply and a sigh before moving on to other (happier) topics.

Last but by no means least to my wife, Mira, for her personal and professional support, motivation, and example. Without your cheerfulness, work/life balance, endurance, inspiration, love of nature, and academic example I would have never finished this thesis. Thank you for the most fantastic 10 years behind us and looking so much forward to the next!

“In this sense, the value of a unit of currency is not the measure of the value of an object, but the measure of one’s trust in other human beings.”

David Graeber, 2011
Debt: The first five thousand years.

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Key concept definitions

Façades-as-a-Service (FaaS)

A model for building envelope procurement in which the building envelope (i.e. façade) builder, and/or the supply consortium behind him, assumes responsibility for the construction, cleaning, maintenance, updating, replacement, decommissioning, and circular material reprocessing of the building envelope and its constituent materials throughout its service life.

Circular Economy (CE)

A circular economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources.

Ellen MacArthur Foundation (2023).

Circular Business Models (CBM)

Circular business models modify the pattern of product and material flows through the economy. By doing so, they can reduce the adverse environmental side-effects resulting from the extraction, use, and eventual disposal of natural resources and materials. This results not only from facility level improvements in material productivity, but also from more fundamental changes in production and consumption patterns.

McCarthy, A., Helf, M., & Börkey, P. (2018). Business Models for the Circular Economy–Opportunities and Challenges From a Policy Perspective. OECD Environment Working Papers.

Product-Service Systems (PSS)

The key idea behind product service systems is that consumers do not specifically demand products, per se, but rather are seeking the utility these products and services provide. By using a service to meet some needs rather than a physical object, more needs can be met with lower material and energy requirements. A product service system is a competitive system of products, services, supporting networks and infrastructure. The system includes product maintenance, parts recycling and eventual product replacement, which satisfy customer needs competitively and with lower environmental impact over the life cycle.

Toepfer, K. (2002). The role of Product Service Systems in a sustainable society. United Nations Environment Programme Division of Technology. Industry and Economics, 1-6.

Methodology definitions

Action Research (AR):

A form of collective, self-reflective enquiry undertaken by participants in social situations in order to improve the rationality, coherence, satisfactoriness or justice of their own social or educational practices, as well as the understanding of these practices and the situations in which these practices are carried out.

Kemmis and McTaggart 1988:5

Total Cost of Ownership (TCO)

A method for calculating the aggregated cost of owning an asset over a determined length of time. This includes the initial purchase or investment price, plus its ongoing capital, operating, maintenance, and eventually decommissioning expenses.

Total Value of Ownership (TVO)

Also known as: Total Value of Opportunity or Total Benefit of Ownership (TBO)

An extension of the Total Cost of Ownership methodology in which the value of the ongoing benefits – both tangible and intangible – of owning the asset are also accounted for. Such values may include directly monetisable factors such as, for example, rental income and (unrealised) property appreciation, as well as more intangible factors such as brand value, future-proofing/risk mitigation of investment, social goodwill, and end-user comfort.

Total Value of Access (TVA)

The sum of all tangible and intangible values and liabilities resultant from having operational access to – but not necessarily legal or economic ownership of – an asset. In an ideal scenario, as a client, one would like to enjoy access to a product-service combination on demand and only during periods in which this access is generating value, while limiting as far as possible exposure to the liabilities connected to this access during periods in which the value or benefit is not being realised.

Designing an Accommodation Strategy (DAS)

An abstract model describing demand, supply and match. It applies to all types of real estate. The proposed strategy design process consists of four phases without any specific sequence:

- determine the mismatch between current demand and current supply
- determine the mismatch between future demand and current supply
- design, evaluate and select solutions to bridge the mismatch
- design the transformation of current supply into selected future supply

Jonge, H. D., Arkesteijn, M. H., den Heijer, A. C., Vande Putte, H., Vries, J. D., & van der Zwart, J. (2009). Designing an Accommodation Strategy (DAS Frame).

Internal Rate of Return (IRR)

A metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/i/irr.asp

Net Present Value (NVP)

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting and investment planning to analyse the profitability of a projected investment or project.
NPV is the result of calculations that find the current value of a future stream of payments, using the proper discount rate. In general, projects with a positive NPV are worth undertaking while those with a negative NPV are not.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/n/npv.asp

Return on Investment (RoI)

A performance measure used to evaluate the efficiency or profitability of an investment or compare the efficiency of a number of different investments. ROI tries to directly measure the amount of return on a particular investment, relative to the investment's cost.
To calculate ROI, the benefit (or return) of an investment is divided by the cost of the investment. The result is expressed as a percentage or a ratio.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/r/returnoninvestment.asp

Opportunity Cost of Capital (OCC)

The incremental return on investment that a business foregoes when it elects to use funds for an internal project, rather than investing cash in a marketable security.

Accountingtools (2023). Retrieved from: https://www.accountingtools.com/articles/opportunity-cost-of-capital-definition-and-usage.html

Discount Rate (DR)

The interest rate used in a discounted cash flow (DCF) analysis. DCF is used to estimate the value of an investment based on its expected future cash flows. Based on the concept of the time value of money, DCF analysis helps assess the viability of a project or investment by calculating the present value of expected future cash flows using a discount rate.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/d/discountrate.asp

Life Cycle Analysis (LCA)

The compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

International Organisation for Standardisation (ISO) standard: ISO 14040.

Life Cycle Cost Analysis (LCCA)

(See also Total Cost of Ownership).

A method for assessing the total cost of facility ownership. It takes into account all costs of acquiring, owning, and disposing of a building or building system.`

Sieglinde Fuller (2016). Life-Cycle Cost Analysis (LCCA) . Retrieved from: https://www.wbdg.org/resources/life-cycle-cost-analysis-lcca

Special Purpose Vehicle (SPV)

Also called a Special Purpose Entity (SPE), is a subsidiary created by a parent company to isolate financial risk. Its legal status as a separate company makes its obligations secure even if the parent company goes bankrupt. For this reason, a special purpose vehicle is sometimes called a bankruptcy-remote entity.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/s/spv.asp

VAT

Belasting Toegevoegde Waarde (BTW) in Dutch.

The Value Added Tax, or VAT, in the European Union is a general, broadly based consumption tax assessed on the value added to goods and services. It applies more or less to all goods and services that are bought and sold for use or consumption in the European Union. Thus, goods which are sold for export or services which are sold to customers abroad are normally not subject to VAT. Conversely imports are taxed to keep the system fair for EU producers so that they can compete on equal terms on the European market with suppliers situated outside the Union.

European Commission (2023). Retrieved from: https://taxation-customs.ec.europa.eu/what-vat_en

Other definitions and abbreviations

TU Delft Campus Real Estate & Facility Management (CREFM) –

Formerly known as “Facilitair Management & Vastgoed” (FMVG)

Abbreviated in this thesis as (TUD) CRE or FMVG, depending on the naming at the time of each publication.

Campus Real Estate & Facility Management (CREFM) develops and manages the real estate and grounds of TU Delft. This includes lecture halls, offices, laboratories, infrastructure and parks on the campus.

TU Delft (2023). Retrieved from: https://www.tudelft.nl/en/about-tu-delft/organisation/university-corporate-office

CiTG

Dutch acronym (Civiele Techniek en Geowetenschappen) for TU Delft’s Faculty of Civil Engineering and Geosciences. In this thesis the acronym generally refers to the faculty’s building at the TU Delft campus, in the city of Delft, the Netherlands.

EWI

Dutch acronym (Elektrotechniek, Wiskunde en Informatica) for TU Delft's Faculty of Electrical Engineering, Mathematics and Computer Science. In this thesis the acronym generally refers to the faculty's building at the TU Delft campus, in the city of Delft, the Netherlands.

Business-to-Business (B2B) and Business-to-Consumer (B2C)

Business-to-business (B2B), also called B-to-B, is a form of transaction between businesses, such as one involving a manufacturer and wholesaler, or a wholesaler and a retailer. Business-to-business refers to business that is conducted between companies, rather than between a company and individual consumer. Business-to-business stands in contrast to business-to-consumer (B2C) and business-to-government (B2G) transactions.

Investopedia (2023). Retrieved from: https://www.investopedia.com/terms/b/btob.asp

Small and Medium Enterprise (SME)

Businesses that maintain revenues, assets, or a number of employees below a certain threshold. Each country has its own definition of what constitutes a small and mid-size enterprise. Certain size criteria must be met, and occasionally, the industry in which the company operates is taken into account as well.

Investopedia (2023). https://www.investopedia.com/terms/a/asset.asp

AEC

Architecture, Engineering, & Construction

CBE

Circular Built Environment

CREM

Corporate Real Estate Management

DBFMO

Design, Build, Finance, Maintain, & Operate

DfD / DfA

Design for Disassembly / Design for Adaptability

EEE

Electrical and Electronic Equipment (sector).

EoL / EoS

End-of-Life / End-of-Service

ESCo

Energy Service Company

E(S)PC

Energy (Savings) Performance Contract

FM

Facilities Management

HVAC

Heating, Ventilation, & Air Conditioning (building services).

ICT

Information and Communications Technology

MEP

Mechanical, Electrical, & Plumbing (building services).

OEM

Original Equipment Manufacturer

PPP

Public-Private Partnership

Summary

Façades-as-a-Service: A cross-disciplinary model for the (re)development of circular building envelopes

Accelerating strategic investment in an energy- and material resource-efficient built environment

The de-carbonisation of the built environment hinges on the use of clean, renewable energy and the conservation of materials and components within circular reprocessing loops. The Façades-as-a-Service research concept aims to accelerate the rate and depth of building energy renovations – while safeguarding long-term responsibility over material resources – by creating a new value-chain based on the provision of integrated building envelopes under a performance contract.

The built environment is a major contributor to the resource management and sustainable development challenges we currently face on a global scale. The rate at which the building stock is improving, in terms of resource efficiency and greenhouse gas emissions (GHG), is far below what is needed to meet even the most conservative climate change and environmental impact mitigation goals (European Commission, Directorate-General for Energy 2020). The strategic investment of limited resources – energetic, material, and financial – which dictates the development of the built environment, is largely driven by individual decision-makers with particular fields of knowledge, specific interests, and acting within diverse time-scales.

Improving the resource-efficiency of the built environment, in terms of the quality of new constructions and the rate and depth of technical building retrofits, is not only a question of technological readiness, but rather of business and economic incentives.

Emerging theoretical frameworks, such as the Circular Economy (CE) and Product-Service Systems (PSS), aim to realign or create these incentives by operationalising the value of better individual decision-making processes, internalising soft values and costs, and developing long-term collaborative project execution mechanisms.

In line with these frameworks, the research elaborates a multi-perspective analysis for a new performance-based investment model to promote the energy transition through the accelerated implementation of high-performance building envelope technologies. Boundaries for the research scope are established, in both technological and managerial ranges, to enhance the applicability of the model and the scientific relevance of the results. Reference is made to specific case-studies, organisations, and regional characteristics, followed by discussions on the implications of such focus groups for the extrapolation of universally applicable conclusions. Finally, the model is evaluated to determine its rate of success at addressing the resource management and environmental impact challenges previously identified.

Results show that, while the implementation of potentially Circular Business Models such as Product-Service Systems is technically possible within the current economic, legal, and managerial landscape, it is by no means a simple or standardised process. Significant systemic changes must take place in order to enable and incentivise the mainstream implementation of performance-based models capable of aligning stakeholder incentives towards more energy-efficient and resource-regenerative building procurement practices. The main bottlenecks towards such innovation are highlighted, and cross-disciplinary recommendations are made regarding the validity, up-scalability, and future development of the proposed methodology.

KEYWORDS Circular Economy (CE), Product-Service Systems (PSS), building economics, real estate management, LIfe-Cycle Cost Analysis (LCCA), Total Value of Ownership (TVO).

Samenvatting

Façades-as-a-Service: Een inter-disciplinair model voor de (her) ontwikkeling van circulaire gevels

Versnellen van strategische investeringen in een energie- en materiaalefficiënte gebouwde omgeving

De decarbonisatie van de gebouwde omgeving hangt af van het gebruik van schone, hernieuwbare energie en het behoud van materialen en componenten in circulaire kringlopen. Het Façades-as-a-Service-onderzoeksconcept beoogt het tempo en de diepgang van energierenovaties in gebouwen te versnellen - met behoud van de langetermijnverantwoordelijkheid voor materiële grondstoffen - door een nieuwe waardeketen te creëren op basis van de levering van geïntegreerde gevels in het kader van een prestatiecontract.

De gebouwde omgeving levert een belangrijke bijdrage aan de uitdagingen op het gebied van grondstoffenbeheer en duurzame ontwikkeling waarmee we momenteel wereldwijd worden geconfronteerd. Het tempo waarin het gebouwenbestand verbetert, in termen van grondstoffenefficiëntie en broeikasgasemissies (BKG), ligt ver onder wat nodig is om zelfs de meest conservatieve doelstellingen inzake klimaatverandering en beperking van de milieueffecten te halen (European Commission, Directorate-General for Energy 2020). De strategische investering van beperkte middelen – energetisch, materieel en financieel – die de ontwikkeling van de gebouwde omgeving dicteert, wordt grotendeels gestuurd door individuele besluitvormers met specifieke kennisgebieden, specifieke belangen en handelend binnen verschillende tijdschema’s.

Het verbeteren van de grondstoffenefficiëntie van de gebouwde omgeving, in termen van de kwaliteit van nieuwe constructies en de snelheid en diepgang van technische aanpassingen van gebouwen, is niet alleen een kwestie van technologische gereedheid, maar ook van zakelijke en economische prikkels. Opkomende theoretische kaders, zoals de Circulaire Economie (CE) en product-servicesystemen (PSS), zijn erop gericht deze prikkels opnieuw af te stemmen of te creëren door de waarde van betere individuele besluitvormingsprocessen te operationaliseren, zachte waarden en kosten te internaliseren, en mechanismen voor langetermijnsamenwerking bij de uitvoering van projecten te ontwikkelen.

In overeenstemming met deze kaders werkt het onderzoek een multi-perspectiefanalyse uit voor een nieuw prestatiegericht investeringsmodel ter bevordering van de energietransitie door de versnelde implementatie van hoogwaardige technologieën voor de bouwschil. Om de toepasbaarheid van het model en de wetenschappelijke relevantie van de resultaten te vergroten worden grenzen voor het onderzoeksgebied vastgesteld, zowel op technologisch als op managementgebied. Er wordt verwezen naar specifieke casestudies, organisaties en regionale kenmerken, gevolgd door discussies over de implicaties van dergelijke focusgroepen voor de extrapolatie van universeel toepasbare conclusies. Ten slotte wordt het model geëvalueerd om te bepalen in hoeverre het succesvol is bij het aanpakken van de eerder vastgestelde uitdagingen op het gebied van grondstoffenbeheer en milieueffecten.

Uit de resultaten blijkt dat, hoewel de invoering van potentieel circulaire bedrijfsmodellen zoals product-servicesystemen technisch mogelijk is binnen het huidige economische, juridische en bestuurlijke landschap, het geenszins een eenvoudig of gestandaardiseerd proces is. Er moeten ingrijpende systeemveranderingen plaatsvinden om de algemene toepassing van prestatiegerichte modellen mogelijk te maken en te stimuleren, zodat de belanghebbenden worden aangespoord tot een energie-efficiëntere en grondstofreducerende aankoop van gebouwen. De belangrijkste knelpunten voor een dergelijke innovatie worden belicht en er worden interdisciplinaire aanbevelingen gedaan met betrekking tot de geldigheid, de schaalbaarheid en de toekomstige ontwikkeling van de voorgestelde methodologie.

TREFWOORDEN Circulaire economie (CE), product-servicesystemen (PSS), bouweconomie, vastgoedmanagement, levensduurkosten, totale waarde van eigendom ("total value of ownership").

1 Introduction

This introduction chapter cites fragments previously published in "Azcárate-Aguerre, J. F., A. Andaloro and T. Klein (2022). Facades-as-a-Service: a business and supply-chain model for the implementation of a circular façade economy. *Rethinking Building Skins*, Elsevier: 541-558."

1.1 Background

The built environment plays a crucial role towards achieving global resource resilience and meeting climate change mitigation goals. The construction and operation of households and infrastructural services is, by a broad margin, the European Union's largest consumer of final energy (41,7%) and Raw Material Input (31%), i.e., domestic material extraction plus materials embodied in imported products. It also contributes to over 60% of the EU's waste generation and 57% of its greenhouse gas emissions (BIO Intelligence Service, 2013, p. 16; Eurostat, 2023a; Eurostat 2023b). These values don't consider manufacturing activities, a significant portion of which also find their final application in, or are supporting industries of, the construction sector and the built environment, see Figure 1.1.

With more than 55% of the global population living in cities – a figure which is expected to rise to 68%, or 6.7 billion people, by 2050 (UN DESA, 2019, pp. 21 & 32) – and with nearly 70% of the buildings expected to exist in European cities by 2050 already built (European Commission. Directorate-General for Energy, 2014) the urge to update the urban built environment is greater than ever before.

The global energy crisis of the early 1970's – caused not by resource scarcity but by geopolitical tension – and the increasing environmental awareness of the last few decades have shifted the attention of policymakers, companies, and consumers towards a more efficient use of resources (Alpanda & Peralta-Alva, 2010; Figueroa, 2013). Parallel to this trend, the focus of policy, science, and innovation in construction has centred on the reduction of buildings' operational energy, mostly through the use of passive and active technologies (Konstantinou & Prieto Hoces, 2018; Sadineni, Madala, & Boehm, 2011).

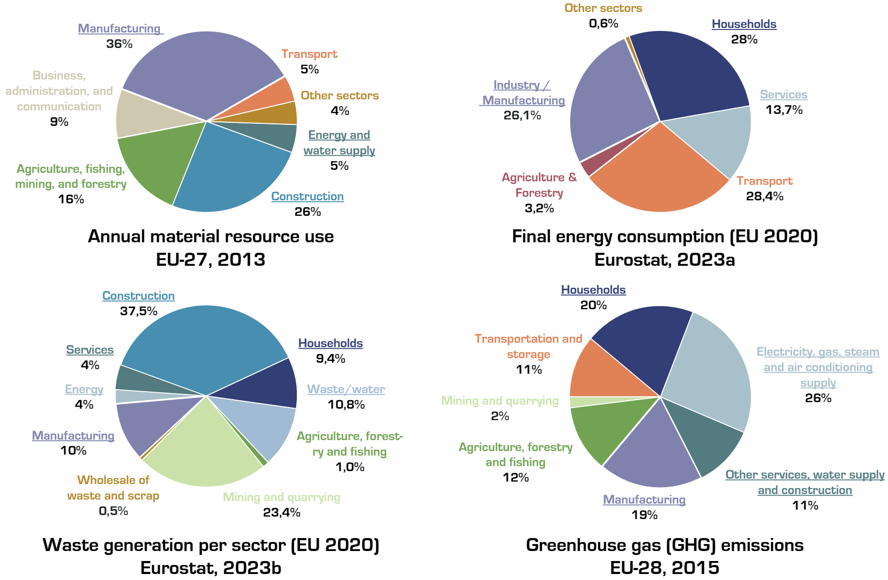

FIG. 1.1 Economic sector statistics for the European Union. (BIO Intelligence Service, 2013; Eurostat, 2023a; Eurostat, 2023a)

Beyond the recognition of energy efficiency requirements in buildings, a more recent trend recognises the growing threat of insecure or unreliable access to material resources. Such challenges had been already recognised by the start of the 1980's (Boulding 1966, Stahel 1982), but mainstream academic (and later industry) attention only shifted toward them since the early 2010's, in part due to the work of the Ellen MacArthur Foundation and its collaborators (Ellen MacArthur Foundation 2013, Webster, Blériot et al. 2013, Webster 2017). As will be further discussed, the clean energy and Circular Economy transitions are closely related. This is particularly the case for the built environment, since the construction of energy efficient buildings relies on large volumes of finite material resources. Even if the entire building stock could be immediately improved from an energy efficiency perspective (which is already impossible in terms of material availability), such improvement would only be temporary as long as systemic mechanisms are not set in place to recover these material resources to enable future construction flows.

Technological readiness, however, does not seem to be the determinant effect towards achieving either a clean energy or a Circular Economy (CE) transition. Even as renewable energy sources and energy-neutral buildings have become a technical reality, investment in such technologies remains concerningly low. Meanwhile, technologies to reprocess and recycle material resources exist, but high-value recovery of building components continues to be limited. In other words, the technological push of scientific and industrial development is not being met by sufficient demand pull from decision-makers in the real estate sector (Jussila, et al. 2022, Langston, Craig, & Weiwei Zhang, 2021, Feige, Wallbaum, & Krank, 2011, Kemi, Mohamed, & Claire, 2007). This lack of demand could be the result of insufficient economic incentives (e.g. relatively low price of inefficiently used energy, materials, and labour). It could also be, as is premise to this research, the result of suboptimal decision-making due to the high (and rising) complexity of building systems and/or the inadequacy and fragmentation of current real estate development and management processes.

1.2 Pre-evidence

The European building stock is relatively old, with more than 40% of it built before 1960, and 90% built before 1990. New construction, following recent energy performance standards, accounts for a yearly addition of 1% to 1.5% to the building stock, while only about 0.1% of the stock is demolished every year (Itard, 2008). This means a major fraction of poorly performing buildings are not being replaced by new ones. With regards to the existing building stock, current deep renovation rates that reduce energy consumption by at least 60% – estimated at around 0.2% per year – are far from sufficient to meet climate-change mitigation goals (European Commission, 2020. pp.3). Furthermore, those renovation projects which are being carried out frequently involve only the aesthetic and functional improvement of their target building, with energy-performance measures being assigned only a small fraction of the typical renovation budget. According to some estimates, only about 1% of renovation projects across Europe can be considered to meet the definition of the Energy Efficiency Directive for deep energy retrofits (Directive 2012/27/EU):

> "Renovations which lead to a refurbishment that reduces both the delivered and the final energy consumption of a building by a significant percentage compared with the pre-renovation levels leading to a very high energy performance" (Artola, Rademaekers, Williams, & Yearwood, 2016, p. 20).

While rising energy prices would provide a greater financial incentive to invest in deep energy retrofitting projects, recent price trends for renewable and non-renewable energy show no such promise in the near future. In fact – and in spite of rising taxation meant to keep energy prices artificially high – the price of electric and thermal energy fell in both real and nominal terms across a number of European countries during the last 15 years (Eurostat, 2017, p. 22). It remains to be seen whether the 2022 energy price increase, caused largely by the aftershock of the COVID-19 pandemic and ongoing geo-political conflict in Europe, will have any long-lasting consequences for energy and resource prices (Ari et al. 2022). Partly as a result of this historically low cost of energy, real estate markets show limited sensitivity to energy performance as a source of increased property value (Holtermans & Kok, 2019, Fuerst, McAllister, Nanda, & Wyatt, 2015). Policy measures, such as enforcing energy labelling during property transactions or strict and prescriptive requirements for retrofitting projects, have contributed to a general decline in heating consumption in the EU built environment, but user awareness, performance-based regulation, and more active involvement of the financial sector remain significant challenges to accelerate progress (Economidou et al. 2020, Galvin, 2012).

Meanwhile, in terms of embodied materials and waste generation, the transition to Circular Economic practices and a regenerative use of materials in the built environment is still only in its early stages. Definitions of effective Circular Economy abound, leading to unreliable or misleading information such as seemingly high rates of material recycling, which upon closer scrutiny include large rates of down-cycling and value loss.

Accelerating both the clean energy and circular economy transitions in the built environment requires a better understanding of the systemic technical and economic factors shaping the development of the construction and real estate sectors.

1.3 Framework

The research combines recent development in Circular Economy theory (the strategic environmental path), Product-Service Systems (the strategic business path), and a critical real estate management approach (the Designing and Accommodation Strategy or DAS model). These research frames are described in further detail below:

1.3.1 Circular Economy

The Circular Economy is a regenerative economic theory seeking to minimise resource input and waste, carbon emissions, and energy leakage by slowing, closing, and narrowing material and energy loops (Geissdoerfer, Savaget, Bocken, & Hultink, 2017). It aims

"to keep products, components and materials at their highest utility and value, at all times" (Webster, 2017)

and to enable a

"flow of materials and the use of raw materials and energy through multiple phases" (Yuan, Bi, & Moriguichi, 2006).

The Circular Economy model is often illustrated by the commonly named "butterfly diagram", see Figure 1.2. The Circular Economy concept is a response to the growing resource challenge faced by companies and industries across a number of sectors and nations, it seeks to restore a balance between economic growth and environmental capacity (Stahel & Reday-Mulvey, 1981, Boulding, 1966).

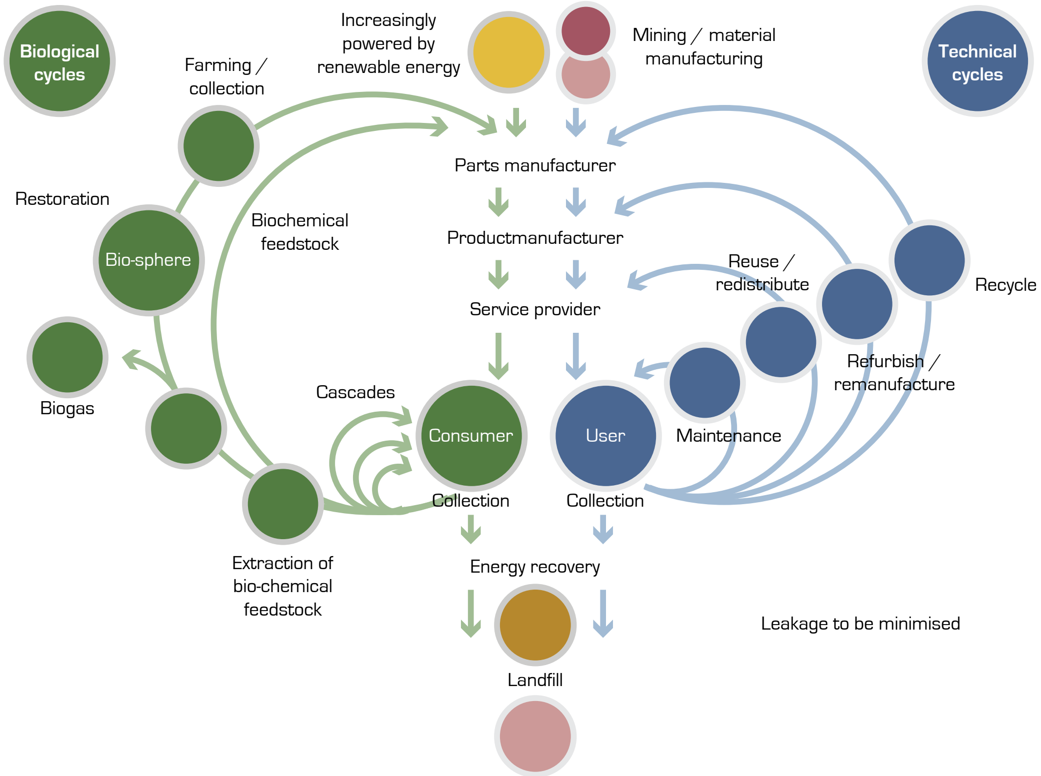

FIG. 1.2 Circular Economy – An industrial system that is restorative by design. (From Webster, Blériot, & Johnson, 2013)

Translated into practical terms, the Circular Economy relies on the revalorisation of so-called “waste-flows” and their generative reintroduction into closed industrial loops. The implementation of a Circular Economy, therefore, relies on the premise that potential value, as well as the possibility of sustainable development, are lost by traditional linear models which are based on disposal and replacement, rather than a hierarchy of service life extension and material recovery strategies. (From Azcárate-Aguerre, Andaloro et al. 2022):

Circular Business Models (CBM’s) are those that focus on the delivery of a value proposition based on regenerative supply chains, reverse logistic channels and extended material value preservation and recovery. They can be categorised into three subtypes, determined by the extent to which they influence or achieve the circularity of resource flows (Bocken, De Pauw, Bakker, & van der Grinten, 2016; Geissdoerfer, Morioka, de Carvalho, & Evans, 2018), see Figure 1.3:

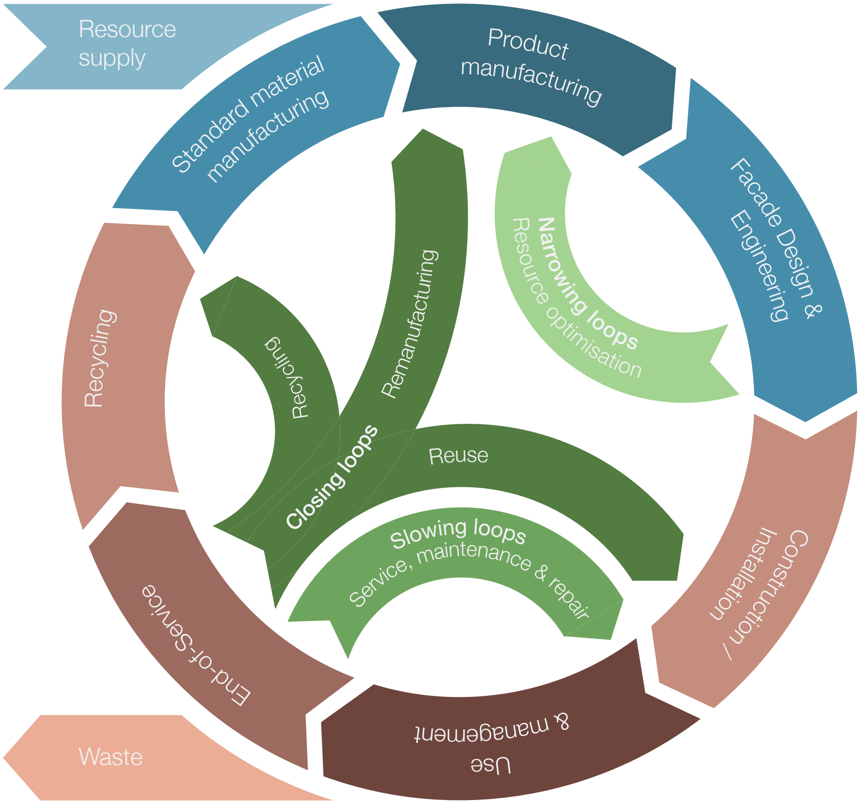

FIG. 1.3 Narrowing, slowing and closing loops in the field of facade design and engineering.

- Narrowing loops focuses on reducing the volume of resources required to fulfil a certain functional requirement. For example, optimising a structure to reduce the volume of steel required. Such models already operate in a linear economy and have limited effect on the circularity of resources as they focus on decreasing volume rather than setting up regenerative flows.

- Slowing loops aims to extend the service life of products to slow down the general rate of resource consumption. PSS fit within this category as they incentivise the production of more durable, higher quality products, the preservation and regeneration of residual value through extended maintenance and servicing, and, thus, the general de-materialisation of economic transactions. PSS create a business environment that facilitates the closing of loops but do not necessarily lead to fully closed and circular systems if the products are eventually discarded or down-cycled due to a lack of economically feasible regenerative alternatives.

– Closing loops relates to the preservation of resources within a closed regenerative system through reuse, re-manufacturing and recycling activities. A PSS circular business model combined with an effective reverse logistics chain and re-manufacturing process can effectively close loops. One of the key overarching challenges to the implementation of 'Closing loops' CBM is the extremely long time-frame within which buildings operate and the fact that it might take decades for us to confirm whether or not today's circular plans translate into truly circular results 15 or 25 years down the road.

Significant investment of material, technical, and financial resources is necessary to effectively achieve the regenerative loops described above. Such investment must work in parallel with systemic cultural and legal frameworks which highlight and safeguard the criticality of material resources to the future of human development. Such new investment and modes of operation are not currently incentivised by the construction and real estate sectors, since none of the main stakeholders in the building construction and operation process can derive sufficient value from them. New forms of project contracting, performance delivery, and value creation must be developed, tested, and up-scaled.

1.3.2 Product-Service Systems

Product-Service Systems (PSS) is the term given to a range of business models which combine the delivery of tangible products and intangible services as a way of fulfilling customers' needs (Tukker, 2015), see Figure 1.4. The concept has evolved in close relation to Circular Economy theory, with a specific focus on industrial economics and business development. In 1982, Stahel emphasised

"selling utilisation instead of ownership of goods as the most relevant sustainable business model for a loop economy, allowing industries to profit without externalising costs and risks associated with waste" (Geissdoerfer et al., 2017; Walter R Stahel, 1982).

The transition to PSS should, in principle, contribute to the servitisation and de-materialisation of industrial practices. This by naturally shifting the core business incentives of suppliers and consumers away from resource consumption and towards revenue models which reward an efficient and regenerative use of human, material, and energetic resources (Tim Baines & Howard Lightfoot, 2013).

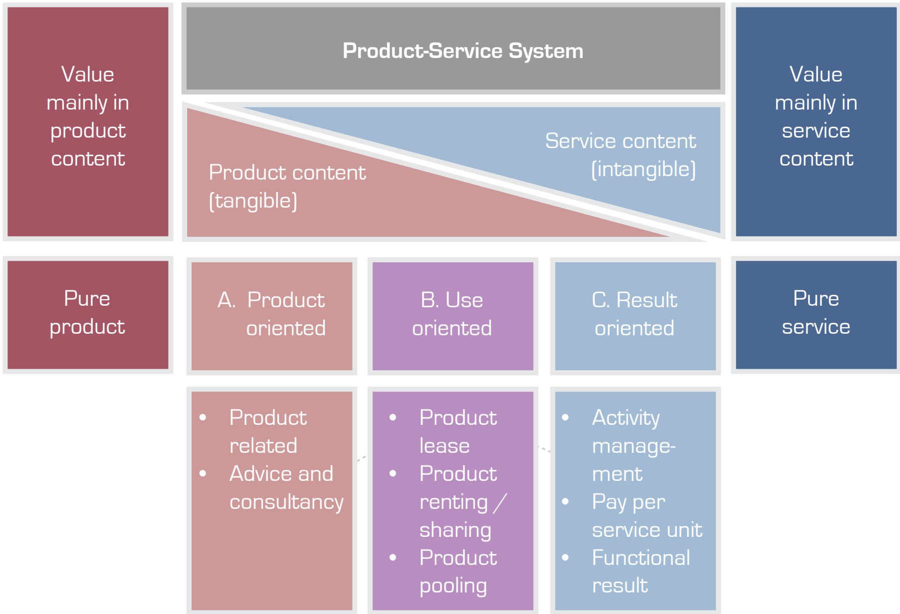

FIG. 1.4 Main and sub-categories of Product-Service System. (From Tukker, 2004)

The categories and strategic objectives of the PSS levels align with the de-materialisation (or regenerative material use) required by the closed Circular Economy model. This has been described in more detail in (Azcárate-Aguerre, Andaloro et al. 2022):

PSS models are a broad category within CBM which aim to gradually shift the value proposition behind business transactions from the transfer of material products to the delivery of performance services. The linear economic system revolves around the transfer of legal and economic ownership of products between parties. These products are used, over a determined length of time, to deliver certain utilitarian results. When the product is no longer capable of delivering these results, or of doing so in an efficient way, they are discarded; most often through low-level recycling or land-filling.

PSS are categorised according to the extent to which transactional value is focused on performance rather than product-delivery. The basic classifications for models currently available on the market are as follows (Cong, Chen, Zheng, Li, & Wang, 2020; da Costa Fernandes, Pigosso, McAloone, & Rozenfeld, 2020; Pergande et al., 2012; Tukker, 2004), see Figure 1.5:

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FIG. 1.5 Broad categorization of product-service systems.

- Product-oriented PSS models deal with tangible products, ownership of which is transferred to the consumer (client), while additional services are offered by the service provider, for example, maintenance contracts.

- Use-oriented PSS models also deal with tangible products, the ownership of which is retained by the service provider who sells product functionalities to the client, for example, car or other equipment leasing contracts. However, in this case the product can also be an intangible asset, for example, content streaming platforms such as Spotify or Netflix. These models are also referred to as access-oriented, as they provide access to customers or end users to the product or service they require, without conveying ownership of the delivering product on to them.

- Service-oriented PSS models emphasise the value of the delivered performance over the tangible assets used to deliver such performance. As in the use-oriented PSS model, the provider retains ownership of the product and then sells the final performance to the client/end user while retaining technical responsibility and economic incentives over how efficiently this performance is delivered. An example of such a result-oriented model would be a scenario in which a building owner hires a certain indoor comfort – based on indicators such as temperature, humidity rate and air quality – for a fixed price, and regardless of how much it costs the provider to install and maintain the equipment needed to deliver this performance.

Applied to the facade industry, Product-as-a-Service models promote long-term relationships between the facade service provider and its supply chain on the one hand, and the final client on the other (Leising, Quist, & Bocken, 2016). It does so by focusing on value creation through ongoing service delivery and shared performance objectives, rather than the traditional procurement and sales contracting mechanism. This responds to a twofold aim: (1) shifting the guarantee over performance to the service provider who has more extensive technical expertise over its products, whereas (2) incentivising a reductive use of materials and other finite resources in the delivery of these performance values (Baines & Lightfoot, 2013; Vezzoli et al., 2017).

1.3.3 Designing an Accommodation Strategy model

In order to determine the match between the demand and supply in the built environment, in the present and future, including the foreseeable future trends on either side of the value chain (Figure 1.6), an analytical framework is applied, also known as the DAS model (Designing an Accommodation Strategy). Within the field of Corporate Real Estate Management (CREM), the DAS model aims to shift the position of strategic property managers from reactive to proactive, by constantly analysing their current portfolio and defining a number of strategic iterations

"by anticipating changes in the processes and activities within the organisation and changes in society as a whole" (De Jonge et al., 2009).

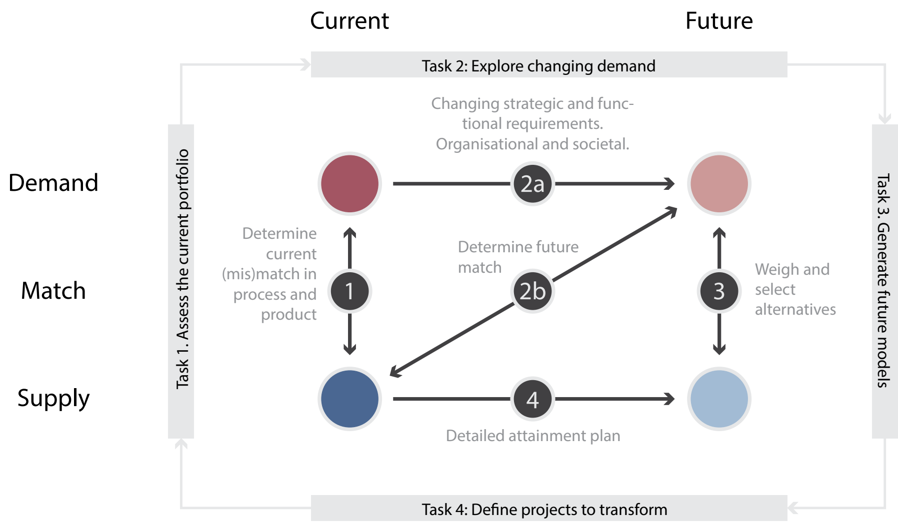

FIG. 1.6 Designing an Accommodation Strategy (DAS) in five steps. Applied in Chapter 7. (Based on De Jonge et al., 2009)

The three strategic approaches described in this section can combine to address the research problem of accelerated clean energy and Circular Economy implementation. A critical approach to real estate development and management can help us whether our needs and objectives align with the project briefings on which our buildings are based. The Product-Service System approach offers a series of alternative business models on which more sustainable and collaborative models of building contracting can be based. The Circular Economy approach provides the overarching motivation and target to achieve faster clean energy retrofit rates without compromising our current and future access to crucial raw materials.

1.4 Research problem

Significant changes are required, in terms of investment models and managerial processes, to support the wider and accelerated implementation of energy-efficient technologies on new buildings, as well as deep energy retrofitting measures on the existing stock. Many studies support the premise that technological readiness is in fact not the main barrier towards reaching an energy-balanced built environment, as the technology to achieve this goal is already available and has been successfully tested (Konstantinou & Prieto Hoces, 2018, Thomas & Duffy, 2013. Instead, the barrier seems to lie in the investment culture and decision-making process driving choices in the construction sector (Kauškale & Geipele, 2017).

The complexity of building (re)development projects leads to inefficient cross-disciplinary information-sharing and collaboration channels (Cleton, 2015; Klein, 2013). This in turn leads to suboptimal technical decisions, which do not take full advantage of technological innovation, nor do they adequately respond to the rising urge to use financial, material, and energetic resources in a more effective or efficient way. This process must be better understood in order to propose alternative solutions, which can realign the long-term interests of the different economic actors which make up the construction value chain. Recent microeconomic theory related to “decision-making architecture” (Thaler & Sunstein, 2009) must be applied to the study of choice in real estate (re)development projects, exploring new ways to inform and improve the long-term strategic perspective of key stakeholders.

A decision-making mechanism and implementation model must be developed to support long-term planning and the efficient allocation of resources. The model must consider that, while energy efficiency in the built environment is the final goal, the rise in complexity of buildings and building systems is necessarily tied to collateral consequences. Many of these consequences are only recently starting to become understood and investigated:

1 The embodied energy and related CO_2 content of operationally energy-efficient technologies is frequently overviewed (Loussos, Konstantinou, van den Dobbelsteen, & Bokel, 2015). While studies show that certain technologies, such as photovoltaic panels, compensate for this embodied energy to deliver a final positive carbon balance (Louwen, van Sark, Faaij, & Schropp, 2016), this is not necessarily the case for all components found in energetically state-of-the-art buildings. As a result, operational energy savings can be significantly offset by the higher embodied CO_2 content of such operationally "low-carbon" technologies (Hildebrand, 2014).

2 From a material perspective, rising complexity also entails rising supply-chain challenges. The high-volume resources traditionally associated with the construction industry such as glass, brick, steel, wood, or gypsum, are increasingly complemented with the low-volume and high-value elements traditionally found in the Electric and Electronic Equipment (EEE) sector. Low-carbon technologies related to the generation, distribution, and storage of energy, as well as to building automation, smart system integration, and the internet of things (IoT) – all of which are frequently considered a prerequisite to an energy-efficient built environment (Fox-Penner, 2014) – are largely dependent on rare and critical materials, the demand of which is constantly rising and presents a new challenge to the future of the clean energy transition (IEA, 2021). Many of these materials are in limited global supply, require a costly, complex and/or highly polluting extraction process, or are otherwise geo-politically sensitive (Abraham, 2015; Moss et al., 2013). The rising material dependency of low-carbon building technologies is illustrated in Figure 1.7 and Figure 1.8 (IEA, 2021).

3 From a financial perspective, the intricate decision-making process driving the initiation and development of construction projects is further compounded by the rising complexity and diversity of building technologies (Asadi, da Silva, Antunes, & Dias, 2012; Tan, Yavuz, Otay, & Çamlıbel, 2016). The financial performance of specific investment decisions (e.g. between low and high energy performance systems) is difficult to quantify from an organisational perspective. Traditional models to calculate Return on Investment (RoI) are often limited to strictly quantifiable sources of cost and income, such as energy savings. They fail, however, to operationalise more abstract and qualitative factors such as human comfort, staff productivity, business streamlining, or sustainable corporate branding. Nor do they internalise "common good" externalities such as environmental damage and carbon emissions (Sauvé, Bernard, & Sloan, 2016).

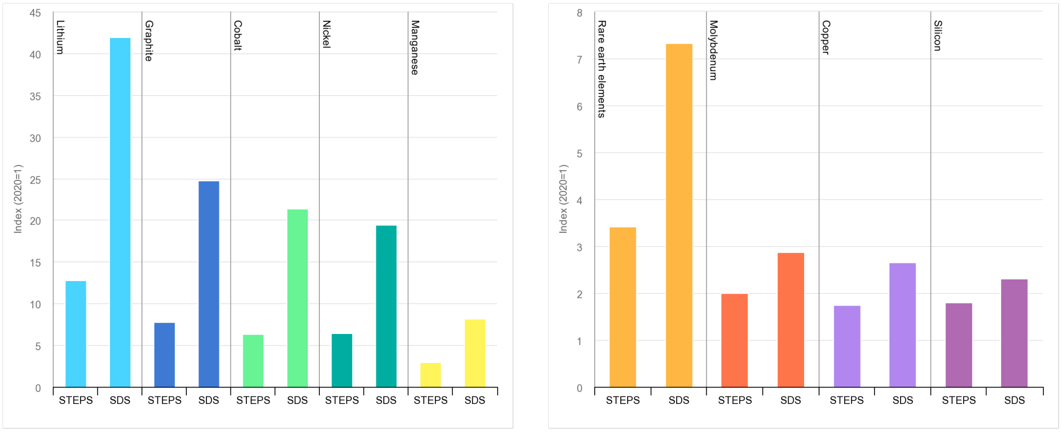

FIG. 1.7 Left: Growth in demand for selected battery-related minerals from clean energy technologies in 2040 relative to 2020 levels by scenario. Right: Growth in demand for selected renewables and network related minerals from clean energy technologies in 2040 relative to 2020 levels. (IEA, 2021)

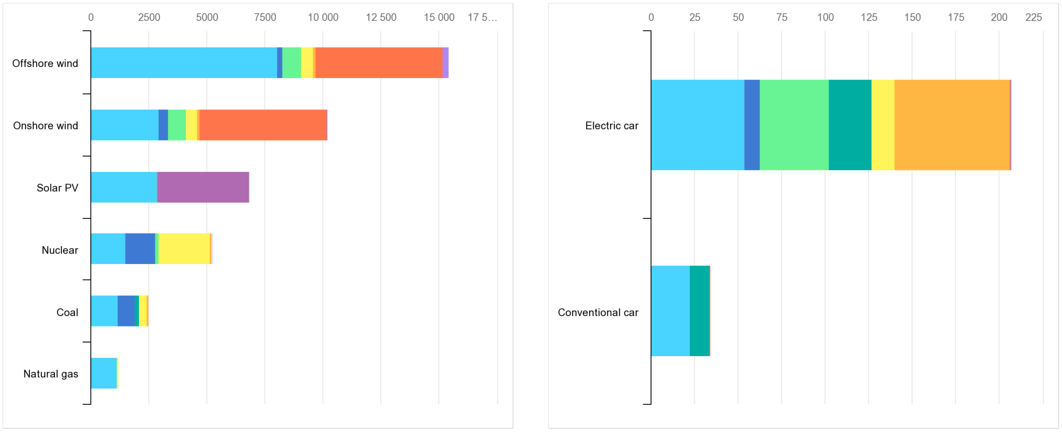

FIG. 1.8 Left: Minerals used in clean energy technologies compared to other power generation sources. Right: Minerals used in electric cars compared to conventional cars. (IEA, 2021)

The research problem lies in the intersection between these different tracks: Embodied energy and CO_2, material resources, and finance. The research sets out to explore how traditional project development and financing mechanisms undervalue and therefore largely ignore the effects of clean energy, embodied carbon, or material resource security. Half a century after Stahel and other authors recognised that the externalisation of such environmental impacts leads to suboptimal decisions and ineffective processing of "waste", our methods for developing, contracting, operating, and decommissioning buildings have not changed (Stahel, 1982, Boulding, 1966). Incentives for more sustainable and long-terminist management of resources are lacking, both at a micro-economic individual decision-maker level, and at a macro-economic policy level. . If technological readiness – as evidence would seem to suggest – is not the key barrier, then the objective of this thesis is to identify which factors are preventing a more organic and widespread adoption of more sustainable practices and business models in the construction sector and the built environment.

1.5 Hypotheses

Based on the background and frameworks stated, this study proposes the following hypotheses:

1. The current – and inadequate – rate of energy efficient construction is not the result of technological or even financial insufficiency, but of ineffective knowledge-transfer and decision-making mechanisms that focus on fulfilling specific project stages rather than providing life cycle-based solutions.

2. A comprehensive methodology for performance-based building envelope procurement, recognising Total Cost of Ownership and cross-organisational values beyond simple energy savings, could accelerate the rate and depth of energy-efficient building envelope construction.

3. Performance contracting models such as Product-Service Systems can provide the necessary economic incentives for the implementation of Circular Economy principles on the design and engineering of building envelopes and their components.

1.6 Research questions

An in-depth analysis of the underlying processes behind decisions affecting the building envelope is needed. This analysis should consider factors such as stakeholder structure, decision-making mechanisms, sources of value and cost, technical alternatives, and supply-chain management strategies. The resulting economic flow-chart can highlight conflicts or inefficiencies in the assignment of resources within the target scope of this research, information which can then be compared against a PSS alternative. This can be summarised into the research question:

- **How can a Product-Service System approach to the contracting of integrated building envelopes be implemented to accelerate the circularity and clean energy transitions in new buildings and deep renovations?**

In order to answer this question a series of sub-questions will define the structure of this research:

- **Chapter 2 | Problem statement:** How does the current process of building envelope procurement hinder the implementation of energy efficient and resource effective façades?
- **Chapter 3.1 | Pilot project one:** *Are decentralised, façade-integrated technologies – and the planning, construction, and management processes behind them – presently capable of delivering the technological solution to the servitisation of the façade industry?*
- **Chapter 3.2 | Pilot project two:** *Are systemic project development, financing, procurement, and management processes presently capable to adopting PSS alternatives? And can this adoption be efficiently and effectively organised under current systemic processes?*
- **Chapter 4 | Drivers and barriers:** Which are the main drivers and barriers, from a multi-stakeholder perspective, to the implementation of Facades-as-a-Service?
- **Chapter 5 | Technology:** What is the role of emerging building technologies on the path towards performance-based contracts and servitisation?

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- **Chapter 6 | Finance:** How can the financial performance of a leased versus a purchased scenario be calculated, considering both tangible and intangible costs and values?

- **Chapter 7 | Management and procurement:** How do current property development, procurement, and management processes result in linear buildings, and which changes must be implemented at a management and business organisation level to achieve circular real estate?

- **Chapter 8 | Conclusions:** How can Circular Business Models (CBM's), such as Product Service-Systems (PSS) be implemented, and could they contribute to a more sustainable façade industry?

1.7 Scope

The strategic investment implementation model at the centre of this research looks at the interests and incentives of diverse economic actors across the construction value chain. It is thus necessary to delimit a scope of research in order to reduce the number of variables and facilitate progress. The boundaries of the research are established on two fields, one technological and one managerial:

1.7.1 Building engineering scope

The technical and economic challenge of improving the building stock is particularly relevant to the design, engineering, fabrication, and management of the building envelope. Depending on the functional complexity and the extent of building service integration, the building envelope can account for between 20% and 40% of the initial financial investment required by a new construction (Parker & Wood, 2013, p. 54) and for about a third of its embodied energy (Hildebrand, 2012). This is illustrated in Figure 1.9. This fraction can be as high as 90% to 100% in the case of deep building retrofitting projects, in which other primary systems such as load-bearing structure, building installations, mobility services, and even interior finishes may be largely preserved (Dall'O, Bruni, & Panza, 2013).

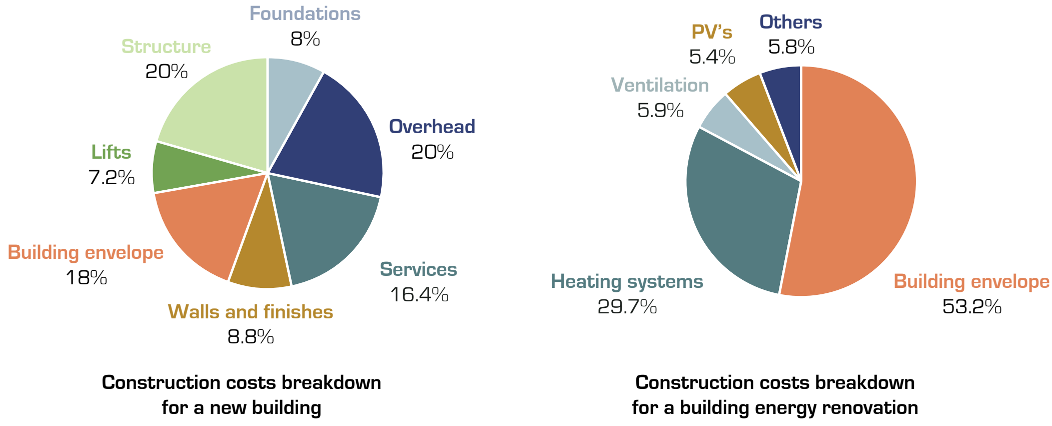

FIG. 1.9 Comparison of initial cost breakdown for a new construction (left) and a deep energy renovation project (right). (Based on data from Van Hoogmoed Architecten, 2014; Dall'O et al., 2013; Klein, 2013; Parker & Wood, 2013)

In terms of operational costs, as well as energy and carbon savings, the influence of the building envelope and services over the entire life-cycle of the building is determinant. Deep building energy renovations can reduce energy consumption across the existing building stock by between 60% and 90% (BPIE, 2011), and a major part of these savings can be attributed directly to the building envelope, or indirectly to the synergy between building envelope and mechanical services (Ebbert, 2010). A reference case-study in the Netherlands assigns 20% of a new project's environmental impact to its façade, and 33% to its building services (Van Hoogmoed Architecten, 2014).

With building renovation projects accounting for approximately 57% of construction activity in the EU, and 82% of revenue in the Dutch façade construction industry (Artola et al., 2016, p. 21; Cleton, 2015; EIB, 2013), it is crucial to find new ways to highlight the diverse values offered by façade engineering and deep energy retrofitting. The proportionally high cost of building envelopes and services, together with a wide range of technical alternatives, render these systems particularly vulnerable to adverse decisions due to planning inefficiencies, budget-cutting, short-termism, or lack of technical knowledge (Klein, 2013).

1.7.2 Real Estate management scope

The real estate management field is widely heterogeneous, with stakeholders across the real estate management spectrum – private, commercial, corporate, and public – being defined by very different economic characteristics, strategic priorities, and value hierarchies. Differences between types of organisation can have a larger impact on their decision-making process than the use category, typology, or functional properties of their building portfolios.

The research is therefore limited not to a defined real estate sector, but to a specific real estate client profile: The institutional developer-owner-utiliser. This group is represented across the property spectrum, but it is predominantly found in the non-residential sector, specifically in the public and corporate segments. As the name entails, this client profile represents long-term owners of buildings who are also actively involved in, or directly responsible for, the development, operation, and utilisation of their property.

Publicly funded universities, governmental organisations, and health-care providers are good examples of (semi-)public clients with non-profit, socially-oriented strategic goals, resulting in a long-term interest in the performance of their portfolio (den Heijer, 2011). Semi-public building owners do not have to prioritise profitability of their building projects, but they do have a responsibility towards society (as taxpayers and end-users) leading the path in terms of sustainability and internalisation of environmental and other societal impacts (den Heijer 2021). Corporate real estate owners, similarly, are companies which develop and manage the buildings they occupy. These buildings therefore act as fixed (operating) assets, and not as a direct source of commercial revenue or core business activity. Corporate property can hence be better understood in contrast to its commercial counterpart: In the commercial real estate sector the development, ownership, management, and exploitation of a property are performed for the final purpose of generating profit. The building project itself is the source of this profit, and not an operating asset through which profit-generating activities can be performed. The life-cycle steps in the commercial real estate sector are therefore frequently held by diverse organisations, who might be active over different time spans and have diverse, and often conflicting, economic interests.

For the residential sector, the study also considers certain semi-public institutional clients, such as housing associations. While not strictly final users of their properties, their long-term interest in their portfolio – as socially-focused real estate operators and exploiters – gives them a similar incentive structure to that of public and corporate non-residential clients.

Figure 1.10 shows the relevance of such client profiles across sub-sectors in the Dutch context. While this profile group is by no means a homogeneous one, further definition and delimitation is elaborated in the relevant section of this thesis (Integrated Façades as a Product-Service System).

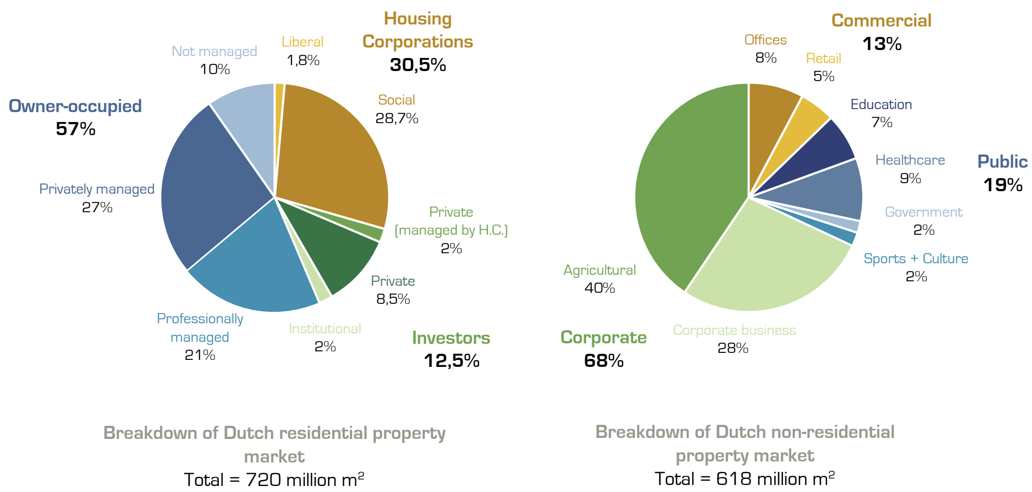

FIG. 1.10 Breakdown of residential and non-residential property per sub-sector in the Dutch real estate market. (Based on data from BZK, 2012; Janssen, Middendorp, de Clerck, & Rieuwerts, 2017)

1.8 Methodology and structure

1.8.1 Action Research Methodology

The Facades-as-a-Service project started in 2015 as a form of interventionist and participatory Action Research (AR) with entrepreneurial intentions. It aimed to test the practical systemic constraints, which prevented the organic adoption of energy- and resource-efficient practices in the built environment in general, and on the building envelope in particular. This objective was an outcome of the author's MSc thesis (Azcárate-Aguerre, 2014), and of the ongoing enthusiasm of academic and industry partners in continuing the research work. From this action research methodology, the intention of the research was to elaborate, together with stakeholders from the demand and supply sides of the construction and real estate sectors in the Netherlands, new business models and best practices that could lead to the adoption of circularity-enabling business models and engineering practices.

This means that the research path presented in this dissertation was not initially structured according to a traditional PhD methodology, nor was it initiated with the objective of performing doctoral research or writing a doctoral dissertation. Only until 2018 was the decision taken to translate the work done into the basis of this PhD methodology, and to continue the remaining work with the parallel objectives of exploring the business potential of the FaaS model, while also developing the multi-stakeholder analytical framework which forms the later building blocks of this dissertation (Chapters 5 to 7).

According to Ioannou, Klein, Konstantinou, Bilow, & Azcárate-Aguerre (2023):

When positioning the Interventionist [Action Research] Approach, Louis Lousberg and Anne van Stijn argue that it oscillates between hypothetical modelling and experimental exploration. The latter, they claim, consists of lab-style methods (cut from the empirical) and design-style methods that explore possible or desirable realities. In this context, prototyping is a design-style method of research intended to generate new knowledge through exploration. It is for this reason that prototyping research falls in the 'Research through Design' modality as an activity "in which design is a substantial part of the process through which new knowledge is created as well as outputs that are proper to disciplinary practice" (Hauberg, 2011).

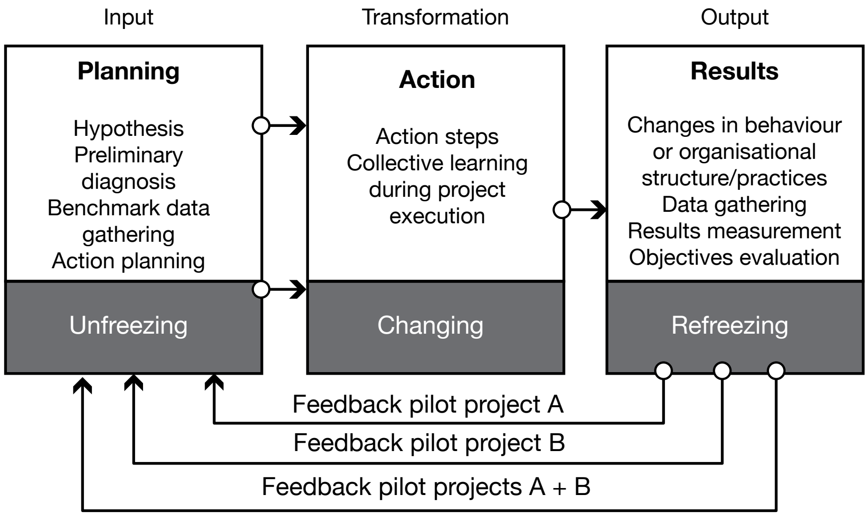

FIG. 1.11 Systems model of action-research process. Adapted from Lewin K. Group Decision and Social Change. New York: Holt, Rinehart and Winston. 1958, p. 201.

Action research thus represents an iterative co-creational process in which an initial hypothesis based on theoretical objectives is tested - through planning, development, and action - against the practical constraints of the present systemic context. The conclusions of this structured action result in feedback loops enabling incrementally effective prototyping, until reliable recommendations to promote societal behavioural changes can be performed (see Figure 1.11). This process is analogous to the Designing an Accommodation Strategy (DAS) model previously described, in the sense that it uses multi-disciplinary participatory iterative feedback loops to critically determine the (mis)match between current and evolving objectives, present processes, and the outcomes that can be expected from (modifications to) these processes.

According to Melrose (2021):

> For community-based action researchers such as Stringer (1996) or organizational-development action researchers such as Palshaugen (1998), rigour in research may mean only that interaction assists the group to extend its understanding of a particular local situation, resolve some of its own problems, and improve the situation under study. Rigour is in the internalized empowering process (within and between the action researchers), not in the perception of any external audience. But even in these situations, the development of descriptive and interpretive accounts of AR may not only assist the group to understand and improve its situation, but it may help those in authority (such as governments or leaders) set better administrative, social, political, economic, or cultural policies.

The two full-scale pilot prototype projects described in Chapter 3 of this dissertation were conceptualised, planned, executed, and evaluated in accordance with this action research methodology. They made use of the collective interest of the participating stakeholders to co-develop two physical, full-scale prototypes, and to question and clarify (from the perspectives of the many stakeholder groups and experts involved) presently unexpected challenges and potential solutions. Chapters 4 to 7 of the dissertation build on the feedback loops facilitated by the pilot prototyping projects, to evaluate from different disciplinary perspectives the present feasibility of the proposed solutions and formulate recommendations to potentially enhance this feasibility.

As stated also in Ioannou, Klein, Konstantinou, Bilow, & Azcárate-Aguerre (2023):

Prototyping as the "shorthand of innovation" also allows stakeholders to develop a deeper understanding of their needs and thus become an integral part of the design process (Kelley, 2007). Prototypes can serve divergent (ideation, synthesis) and convergent (evaluation, selection) purposes, respectively, in a product development process (Jensen et al., 2016). Prototypes are "an approximation of the product along one or more dimensions of interest" (Ulrich & Eppinger, 2007). In this light, prototypes are devices also used to communicate design research; they are carriers of knowledge and meaning (Stappers, 2007). In addition, the choice of materials, their modes of production and ways of interacting with the prototype embody a practical interest connected to the broader context in which the prototype is situated. Prototypes represent the intentionality of the designers and their objectives; therefore, prototypes – just like any type of research – are never ethically or politically neutral (Till, 1992). The description of the context is vital for understanding the prototype.

Table 1.1 provides an overview of the organisations involved in this iterative process, and the disciplinary perspective they represented.

TABLE 1.1 Summary of the organisations involved in the Facades-as-a-Service research, through action research targeting the co-development and construction of full-scale FaaS prototypes according to present systemic constraints.

Disciplinary field	Organisation	Perspective
Strategic (real estate) management	TU Delft Campus Real Estate. Project development and facilities management.	Practice. Problem-owner. Property development and facility management.
	TU Delft Board of Directors	Practice. Problem-owner. Institutional strategic governance.
	TU Delft Faculty of Architecture and the Built Environment. Department of Management in the Built Environment.	Academia. Innovation in management of the built environment.
Project finance	TU Delft Campus Real Estate. Finance.	Practice. (Real estate) project financing.
	TU Delft Central Finance Department	Practice. Institutional financing and financial management.
	ABN AMRO Lease	Practice. Large banking institution, lease branch. Project financing.
	Rabobank	Practice. Large banking institution. Project financing.
	PricewaterhouseCoopers (PwC)	Practice. Third-party consultancy, real estate valuation.
Governance and building law	TU Delft Campus Real Estate. Legal.	Practice. Building and procurement legal advise.
	TU Delft Central Legal and Procurement Department	Practice. Institutional legal and procurement governance.
	TU Delft Faculty of Architecture and the Built Environment. Department of Management in the Built Environment.	Academia. Building law and policy.
	Houthoff	Practice. Dutch top-tier multi-expertise law firm.
Technological readiness	TU Delft Faculty of Architecture and the Built Environment. Department of Architectural Engineering + Technology.	Academia. Façade engineering, building product and process innovation, sustainable technologies and practices.
	Dutch Metal Windows and Facades Branch Organisation (Vereniging Metalen Ramen en Gevelbranche, or VMRG)	Practice. Organisation of suppliers and builders in the Dutch metal façade industry.
	Alkondor Hengelo B.V.	Practice. Dutch façade builder with circularity and product-service systems strategic motivations.
	Consortium of façade systems and components suppliers.	Practice. Consortium of façade systems and components suppliers.
	Office Vitae	Practice. TU Delft start-up and research spin-off developing subjective and objective indoor comfort monitoring processes.
	TU Munich School of Engineering and Design. Building Technology and Climate Responsive Design	Academia. Indoor climate and energy performance simulation and calculation.

The process for involving stakeholders followed an organic path, in which the research and/or project execution branches behind the pilot project development would realise a missing piece of information was preventing progress, and academic or professional expertise would be searched depending on the nature of the question. Outcomes of such discussions were recorded in logbooks, summarised and discussed with all participants during the following general consortium meeting. In many cases, in particular for the CiTG pilot project, several discussions related to project financing, impacts on property valuation, legal structure possibilities, among many others, were recorded through group email threads. These email threads are part of the project archive and have been used in the preparation of the papers which form the body of Chapters 4 to 7. These exchanges provide the overview of the challenges faced, and the eventual solutions discussed and/or selected.

Throughout this process the role of the author, and his academic tutors, was to engage and then maintain stakeholder involvements, structure the research and execution objectives of the projects into fields of study and specific questions which needed to be answered to determine the FaaS model's feasibility, and to a certain extent to mediate between stakeholders used to operating under commercial – and often conflicting – interests. This role of the researcher not only as observer but as motivator, mediator, and translator would be an interesting outcome of the action research method applied and will be discussed further in the reflection in Chapter 8.

1.8.2 Research Structure

The research explores the feasibility of a performance-based business model for the contracting of circular Facades-as-a-Service. It does so by:

1. Establishing the relevance of PSS models, such as Facades-as-a-Service, as a strategy to optimise the construction sector's use of resources, and reduce the environmental impact of the built environment.

2. Developing full-scale prototypes, in close collaboration to key stakeholders and decision-makers, to identify drivers and barriers to implementation in real practical settings.

3. Categorising drivers and barriers, from the perspective of key stakeholder disciplines (technology, management, building law, and project finance), for the implementation of such PSS models.

4. Analysing the results of the prototypes and proposing solutions to promote the implementation and standardisation of PSS models.

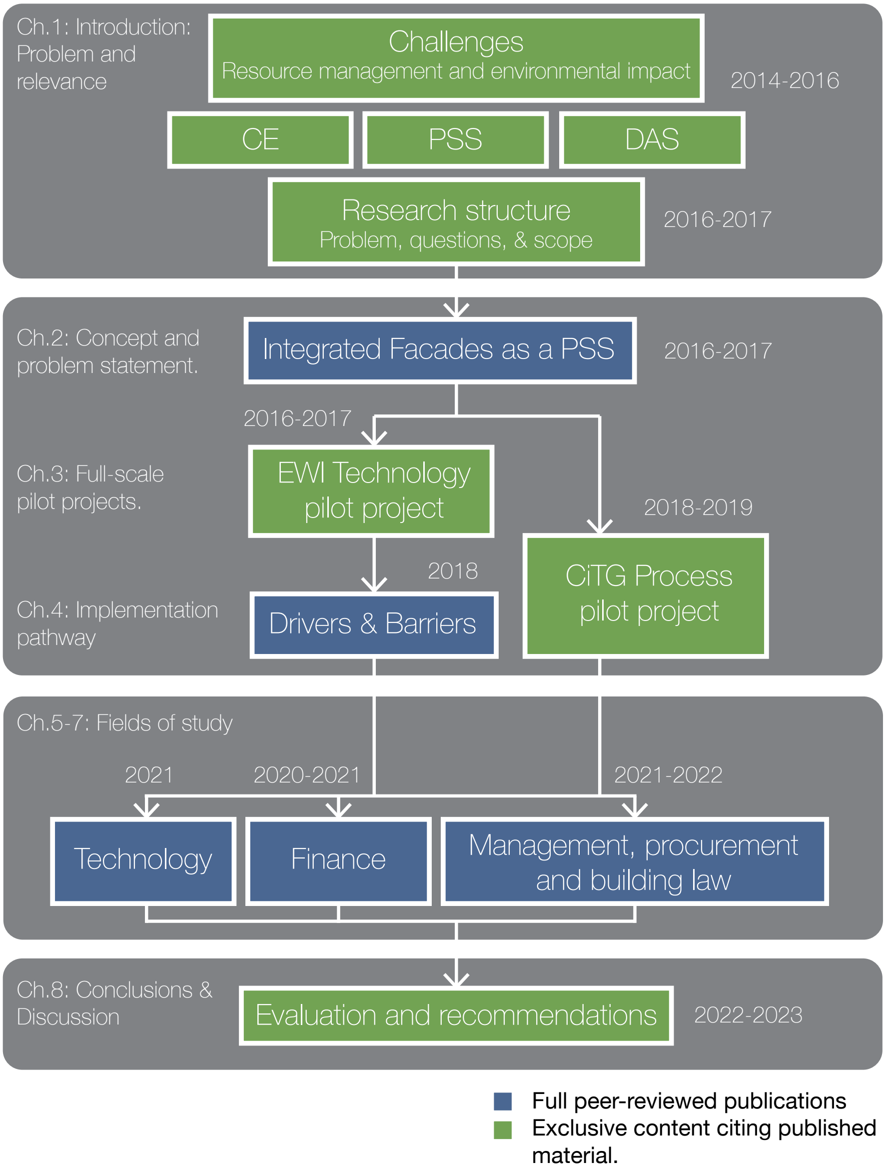

FIG. 1.12 “Façades-as-a-Service” research structure.

TOC

Figure 1.12 shows the research structure and time-line:

An integrated, comprehensive model to better understand the impact of technical, financial, and managerial decisions on the Total Cost and Value of Ownership of a building project can support the implementation of Product-Service Systems into the construction industry. A shift towards PSS can set the economic foundations for the development of more circular design and engineering choices across the supply chain. Focus should not be on the sale of products in a predominantly lower-cost-driven market, but rather on the efficient and ongoing delivery of long-term services (Azcárate-Aguerre, Den Heijer, & Klein, 2017; Sauvé et al., 2016).

Research is conducted through a combination of literature study, semi-structured interviews with relevant stakeholders, qualitative and quantitative calculations, and iterative full-scale prototypes. Chapters 1 to 4 intend to understand the scale of the problem, define a mitigation strategy, and recognise drivers and barriers to implementation; Chapters 5 to 7 involve the analysis of data, as well as the design and engineering of solutions specific to the selected case-study buildings; Chapter 8 condenses the findings of the previous chapters into a practical implementation plan followed by a process evaluation and discussion.

This dissertation collects published work from the following peer-reviewed sources and published project reports:

Chapter 1: Introduction
Azcárate-Aguerre, J. F., A. Andaloro and T. Klein (2022). *Facades-as-a-Service: a business and supply-chain model for the implementation of a circular façade economy*. Rethinking Building Skins, Elsevier**:** 541-558.

Chapter 2: Integrated Façades as a Product-Service System
Azcárate-Aguerre, J. F., A. C. Den Heijer and T. Klein (2017). *"Integrated Façades as a Product-Service System: Business process innovation to accelerate integral product implementation."* Journal of Facade Design and Engineering 6(1).

Chapter 3a: On the use of full-scale pilot projects in this research:
The TU Delft EWI Facades-as-a-Service technology pilot project
Azcárate-Aguerre, J. F., T. Klein and A. C. den Heijer (2016). *A business-oriented roadmap towards the implementation of circular integrated façades.* 9th International Conference Improving Energy Efficiency in Commercial Buildings and Smart Communities, JRC Science Hub**:** 463-473.

Azcárate-Aguerre, J. F., T. Klein and A. C. den Heijer (2016b). Integrated Façades as a Product-Service System: An innovative business model for the implementation of Circular Economies in the construction industry. Delft, Delft University of Technology

Chapter 3b: On the use of full-scale pilot projects in this research:
The TU Delft CiTG Facades-as-a-Service Management pilot project
Azcárate-Aguerre, J. F., T. Klein and A. C. den Heijer (2020). *Façade Leasing Demonstrator Project: Final Business Delivery Report.* Delft, Delft University of Technology.

Chapter 4: Drivers and barriers to the delivery of integrated Facades-as-a-Service
Azcárate-Aguerre, J. F., T. Klein, A. C. Den Heijer, R. Vrijhoef, H. D. Ploeger and M. D. I. Prins (2018). "*Façade Leasing: Drivers and barriers to the delivery of integrated Facades-as-a-Service.*" Real Estate Research Quarterly **17**(3).

Chapter 5: The technological dimension
Azcárate-Aguerre, J. F., T. Klein, T. Konstantinou and M. Veerman (2022). "*Facades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope.*" Applied Sciences 12(3): 1267.

Chapter 6: The financial dimension
Azcárate-Aguerre, J. F., M. Conci, M. Zils, P. Hopkinson and T. Klein (2022). "*Building energy retrofit-as-a-service: a Total Value of Ownership assessment methodology to support whole life-cycle building circularity and de-carbonisation.*" Construction Management and Economics: 1-14.

Chapter 7: The management dimension
Azcárate Aguerre, J. F., Den Heijer, A. C., Arkesteijn, M. H., Vergara, D. A., & Klein, T. (2023). *Facades-as-a-Service: Systemic managerial, financial, and governance innovation to enable a circular economy for buildings. Lessons learnt from a full-scale pilot project in the Netherlands.* Frontiers in Built Environment, 9, 55.

1.9 Scientific and societal relevance

The novelty of this research lies in the integration between a technical building envelope engineering and iteration process, and a comprehensive analysis of the economic and managerial context in which decisions between these iterations are made. The supply push of technology is evaluated against the demand pull of real estate management. The practical applicability of the research findings, under current market conditions, constitutes its scientific and industrial relevance. While the Circular Economy is by no means a new concept, and it has been referred to in one form or another for decades (Boulding, 1966; Pearce & Turner, 1990; Walter R Stahel & Reday-Mulvey, 1981), practical translation of its principles into actual industrial operations is still rare. More concerning still, growing marketing trends focusing on “circularity” threaten to dilute the true meaning of the term, and produce both science and products which do not truly address the goals of CE theory, or which do so only superficially (Valenzuela & Böhm, 2017).

It is axiomatic to this research that a transition towards circular material flows is needed to enable continuous global development at a rate anywhere near that of the last two centuries. To achieve this, this research proposes, it is necessary to look beyond the design and engineering of circular products within a persistently linear system. Such a strategy often ignores the fact that these products do not exist in an economic vacuum, and design intent does not always translate into real impact. Instead, focus should be on the systemic business and economic model supporting the transition in a specific industry and sector (Lieder & Rashid, 2016). Once this new economic structure is built, and the expectations and drivers for the different economic actors aligned, the engineering and design of circular products can follow.

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2 Integrated Façades as a Product-Service System

The chapter builds on the ideas developed in the author's MSc thesis: "Azcárate-Aguerre, J.F. (2014). *Façades as a Product-Service System: The potential of new business-to-client relations in the facade industry* MSc thesis, Delft University of Technology.", and has been published in "Azcárate-Aguerre, J.F., A.C. Den Heijer and T. Klein (2017). "Integrated Façades as a Product-Service System: Business process innovation to accelerate integral product implementation." *Journal of Facade Design and Engineering* 6(1)."

ABSTRACT The Circular Economy (CE) attempts to realign business incentives, across all fields of human industry, to support the preservation of raw materials within closed economic loops. Within this conceptual frame, Product-Service Systems (PSS) combine the use of tangible products such as building technologies, with intangible maintenance and monitoring services, to enhance the delivery of valuable performance while limiting the use of materials and other finite resources. This paper explores the potential for the application of CE and PSS organisation principles in the delivery of Façades-as-a-Service. It explores how the benefits brought about by this way of thinking - lower initial capital requirements, material ownership retention by suppliers, and long-term interdisciplinary collaboration - could lead to a more efficient façade construction industry, while accelerating the rate and depth of building energy renovations.
Within the current process for designing, manufacturing, and operating façades there is a gap between supply-side discoveries and demand-side needs, which hinders the implementation of resource-efficient façades. Façade-leasing as a form of product-service system keeps suppliers committed, throughout the building's service-life, to safeguard optimum performance in operation, while actively stimulating clients to adopt innovative technical solutions.
The paper elaborates on both supply-side façade innovations and the demand-side conditions necessary to implement such business models, and also explores the costs and benefits of product-service systems as new collaboration models to align supply and demand incentives. It builds upon the research project "Façade leasing" (Azcárate-Aguerre, 2014) and combines knowledge about façade design

and engineering (supply-side approach) with the knowledge about client needs, performance criteria, and willingness to pay (demand-side approach). The research methodology includes a literature review and expert interviews, integrating both theory and practice.
This paper argues that a Product-Service System approach to façade design, construction, operation, and renovation could accelerate the rate and depth of building energy renovations. It could also provide incentives to supply- and demand-side stakeholders, to implement Circular Economy principles through new models of product ownership, service contracting, and performance delivery. It aims at establishing the general conceptual frame of a Product-Service System for leasable façades, setting the basic parameters to be considered when designing a PSS-based business model, and formulating its value proposition.

Chapter summary

This chapter describes how traditional building envelope contracting models lead to inefficiencies and missed opportunities in the transition to a more energy- and resource-efficient built environment. It then introduces the Façades-as-a-Service concept, its origins, argumentation, interdisciplinary nature, and relation to energy efficiency and material circularity goals. Comparisons are drawn from other economic sectors, in which product-service systems have a longer development history. A façade-as-a-service organisational model is described, and the necessary evolution of stakeholder roles is proposed.

A focus on the reduction of operational energy consumption in buildings, over the last few decades, has led to significant innovation in façade and façade-integrated components (Konstantinou & Prieto Hoces, 2018). Passive methods to improve the thermal performance of the building envelope, combined with active technologies for energy production and storage, decentralised air management, automated windows and sun shading, among others, result in façade systems capable of delivering most of the indoor climate requirements of a target building.

The slow rate of implementation of such systems, however, points to market entry barriers beyond simple technological readiness (i.e. supply-push mechanisms). Instead, barriers to the energy transition in general, and to the implementation of integrated façades in particular, lie in market-pull mechanisms. Among these mechanisms are inadequate managerial processes, investment culture, decision-making practices, contracting structures, governance, and corporate business models (BPIE, 2011, p. 55).

A shift in façade contracting mechanisms, from a linear system based on the delivery of products, to a circularity-enabling system based on the ongoing delivery of indoor climate and comfort services, has the potential to address many of the systemic problems currently preventing wider adoption of more effective and technically advanced building envelopes. The creation of a new value chain for façade contracting – based on shared long-term incentives among all involved stakeholders – could lead to faster and deeper façade interventions in both new constructions and building retrofitting projects. It could also improve the strategic economic and business position of companies across the value chain and reduce the shock of economic and real estate market cycles, thus leading to faster and steadier energy and circularity transitions.

2.1 Introduction - How does the construction process hinder the implementation of energy saving measures and components?

The last few decades have seen an exponential development in the field of energy conservation and generation technologies within the construction sector. Goals for the reduction of CO_2 emissions, established by the EU for the years 2020 and 2050, have set a strong regulatory frame for the implementation of such technologies in all fields of architectural and infrastructural development. As a result, many organisations with large real estate portfolios – such as universities, hospitals, and financial institutions – have signed agreements in the past decade to reduce their ecological footprint and stimulate resource-efficient projects (ABN AMRO, 2014; den Heijer & Teeuw, 2011; Joustra, de Jong, & Engelaer, 2013; ING, 2015). However, the mass-market implementation of energy-efficient products is being negatively affected by the traditional business and supply processes that dominate the construction industry (Vrijhoef, 2011). Innovative business models and contracting mechanisms are required to support and accelerate the market absorption of energy-efficient technologies in the industry, share the performance risks (and benefits) of innovative products, and enhance the financial accessibility of performance-based renovations (Gondrie, Klein, Den Heijer, & Konstantinou, 2015). This would upscale the impact of upcoming technologies on the reduction of CO2 emissions, by facilitating their market-wide implementation. In other words, innovative business and management processes are required to act as a catalyst for the accelerated implementation of innovative technological products.

Despite the current technological capacity to produce energy-neutral and even energy-positive buildings (Marszal & Heiselberg, 2011) the real-life application of these technologies is still limited to a relatively small segment of high-performance, high-cost, iconic, and experimental constructions (Banfi, Farsi, Filippini, & Jakob, 2008). Low-energy buildings – though highly significant from a scientific and marketing perspective – are still a small fraction of the European building stock. The main hindrance to the wider utilisation of such systems lies in the incentive structure that dominates the industry, as short-term stakeholders are offered no direct incentives from the long-term operational benefits provided by their products (Van Nederveen & Gielingh, 2009; Vrijhoef, 2011).

Direct operational benefits from energy savings must be complemented by the multi-stakeholder incentive structure proposed by a Circular Economy systemic approach. In the current, product-centred transaction structure, stakeholders involved in the construction and operation of a building have short-term participation in the project based on the sale of components. A transition towards a service-based structure, founded on the long-term collaboration between project partners with shared performance goals, will more effectively create shared value while improving a building's performance and ecological impact from an energy and raw material consumption perspective.

Many of the theoretical assumptions presented in this paper have been extrapolated from better-documented examples belonging to other manufacturing industries, as this is a relatively unexplored topic in the construction industry. This study builds upon these examples to establish a value proposition for new models of collaboration, by outlying the theoretical costs and benefits of a long-term, Product-Service System (PSS) for the delivery of Façades-as-a-Service. This is done from the point of view of both supply and demand side stakeholders. In order to evaluate this proposition, we combine, on the one hand, a Building Technologies approach to describe upcoming technological products, as well as their potential impact on a building's energy performance. On the other hand, we assess, from a Real Estate Management perspective, the value these product-service combinations could represent for a (client) organisation. This is based on their contribution to the organisation 's functional, financial, strategic and sustainability/energy goals (den Heijer, 2011, 2013), see Figure 2.1.

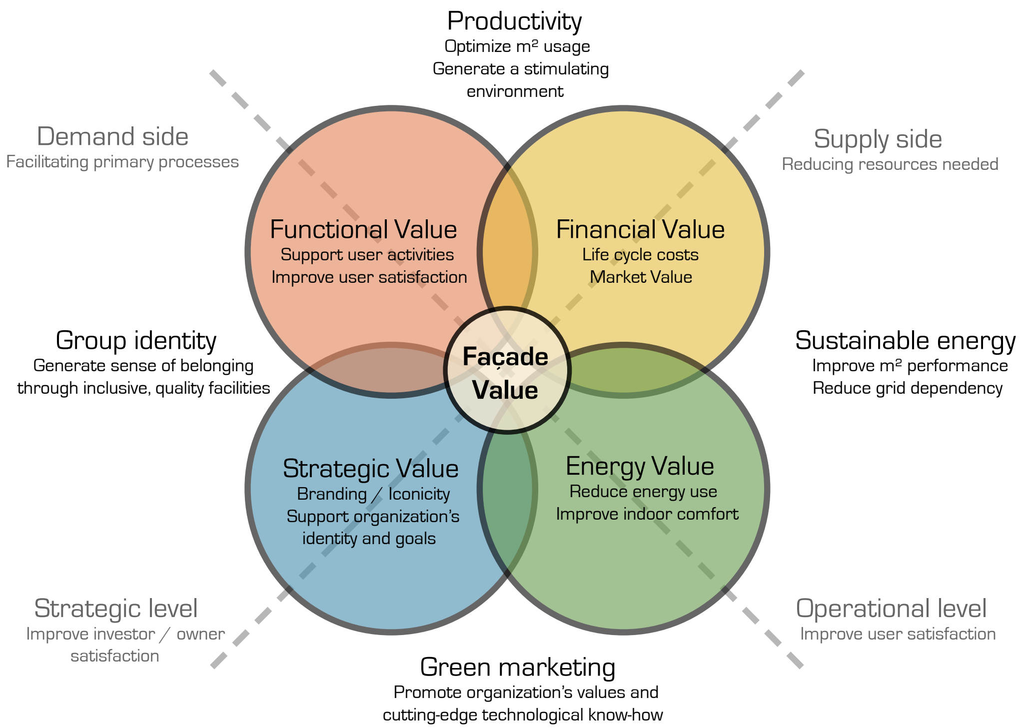

FIG. 2.1 "4-value" performance criteria for determining added value for clients and end-users of real estate. (Adapted from Den Heijer, 2013 based on real estate management theory (den Heijer, 2011))

This paper proposes that the general focus on short-term financial gains (or losses) that currently dominates decision-making, often results in missed opportunities to collaboratively extract long-term value in the functional, strategic, and energetic fields, while also preventing the implementation of circular resource management and conservation strategies. It explores the ways in which the current supply process hinders the application of new, and more efficient, building products and technologies (2.2 Problems in the current construction process). It then explores the supply-side challenges and opportunities (2.3.1 Product-Service Systems as an industry-transforming strategy – The business and supply solution), as well as the demand-side requirements and interests that must be considered (2.3.2 Integrated Façades – The technological solution) in order to determine the brief for new business-to-client models that encourage innovation (2.4 Conclusions). The objective is to outline the changing role of stakeholders, the added value for demand and supply sides, and, lastly, to define further necessary research along these lines.

2.2 Problems in the current construction process

The current construction industry is characterised, as are many other manufacturing industries, by a strong linear process (Joustra et al., 2013; Vrijhoef, 2011). The flow of materials, services, and knowledge through the supply chain is largely interrupted at every step of the process, as long-term collaboration between supply tiers, contractors, and clients is hardly promoted by current contracting methods (Vrijhoef, 2011). The general tendency to look at buildings as “finished products” rather than “ongoing processes” leads to an overall short-sightedness when defining the most efficient operation and end-of-service scenario design for the construction and the materials that compose it.

A failure to define long-term goals that can be shared by all stakeholders (on the supply and demand sides), results in a process that assigns a high value to materials – as materials and components are the elements being traded between stakeholders – while underestimating the value of services (or capabilities) delivered by or through such products. We have identified two primary mechanisms embedded in the construction process that contribute to a fragmented supply-chain and a slow technological progress curve. These are further described below as: 1.3.1 Business and supply mechanism, and 1.3.2 The technological innovation mechanism.

2.2.1 Business and supply mechanism

The rate of innovation, development, knowledge transfer, and implementation – in other words, the technological life cycle – of the construction industry is relatively slow. This section elaborates on those negative circumstances, which lie within the business and supply practices of the construction industry: (A) The industry structure, and (B) The small scale of supply companies.

A **The industry structure:** When compared to other manufacturing industries (such as automotive and consumer electronics), the construction industry stands out for its general lack of central coordination (Van Nederveen & Gielingh, 2009; Vrijhoef, 2011). A central driving force, in this context, is defined as a stakeholder with incentives to optimise the entire production process – from design through fabrication, operation, and end-of-service reprocessing – who has clear leverage on suppliers and subcontractors, and therefore the power to reshape the entire supply chain towards more efficient or sustainable practices. As a reference, automobile manufacturers act as central driving forces throughout the entire process from the design to the collection/reprocessing of a car, even when they may not be necessarily responsible for individual steps in the process such as designing and manufacturing individual components, or providing aftermarket servicing and maintenance. Their crucial role in the production of the car, in terms of design, assembly, branding, and even financing, provides them with an important leverage to re-define their processes and demand suppliers to follow their guidelines. As established by the principles of "lean manufacturing" (Womack, Jones, Roos, & Massachusetts Institute of Technology., 1990) this long-term relationship between the product assembler/marketer and component suppliers promotes innovation and efficiency by setting common and extended performance-oriented goals throughout the supply-chain.

In the construction industry, however, there are two major conflicts that prevent the application of such processes. On one hand, the supply-chain, consortium, and contracts differ from project to project (Vrijhoef, 2011). They are as customised as the individual projects they are related to, which hinders standardisation in collaboration approach or product solution (Gjaltema, Laterveer, & Vrijhoef, 2013). Therefore, the risks associated with the implementation of innovative solutions are relatively high, as supplier involvement after the realisation of the project is generally limited to a series of operational guarantees. On the other hand, none of the individual stakeholders collaborating in the construction process has enough leverage to demand substantial changes, in terms of practices and methods, from the other parties involved in the project. A possible exception to this would be the client, who could decide to maintain active involvement in the process as a decision-maker, but whose technical knowledge would generally be insufficient to demand significant structural changes. A shift towards a more active participation from clients and investors has been recently recognised. Real estate developers and managers such as Delta Development Group (Scott, 2015), and banking institutions such as ABN AMRO (ABN AMRO, 2014), are taking steps to improve the long-term health and sustainability of their projects and investments.

B **The small scale of supply companies:** Façade suppliers and producers, worldwide, are in general relatively small companies (Cleton, 2015). The typical project portfolio of one of these producers could comprise between 10 and 20 projects of varying sizes, at any given time. This means that a problem with product-delivery or guarantees in any given project can have a substantial negative effect on the overall yearly performance of the company (and can have devastating consequences when accentuated by times of financial crises). This currently results in a façade industry that is overly cautious when it comes to implementing new technologies with a limited testing history. Instead, systems with which suppliers and contractors are familiar are chosen, and which have been proven consistently over time, even if these systems are below the state-of-the-art in terms of energy efficiency or other performance criteria. Consequently, the small scale hinders innovation, as SME suppliers cannot often afford to deviate from traditional solutions, or are prevented from doing so by market forces or decision-makers further up the value chain.

On the positive side, a small project portfolio means that SME suppliers are likely to be interested in implementing new business models, which extend their involvement in projects and ensure a long-term, steady source of revenue. This is in contrast to a product-delivery-based business structure, which forces them to constantly look for new clients and projects in order to secure a highly volatile cash-flow.

2.2.2 The technological innovation mechanism

Next to the structural disablers that the construction industry brings from a business and supply perspective, there are technological obstacles that affect the market-integration of innovative products: A) The rate of effective technology implementation and B) Risks and uncertainties for the client.

A **The rate of effective technology implementation:** The rate at which technological innovation can occur within a system is, necessarily, closely tied to the length of its (effective) implementation cycle, also known as its “vital life” (Arthur D. Little, 1981). By an effective implementation cycle we mean the time it will take between the creation of the first working prototype of a technological product, and the moment in which this product reaches the mature economy of scale, in production, which would facilitate its mass-market application. This rate is also tied to the expected service-life of the previous generation of an equivalent product, as few users will replace a system before it is technically (or in some cases socially) required. For example, Smartphone suppliers are able to make modifications to their platforms at a rate of one or even two new releases per year, because the market absorption and expected service-life of these units is, on average, 18 to 24 months. In this specific case, replacement rarely comes as a technical obligation, but is generally due to trends, marketing, and other social behaviour. In the case of façades and façade-integrated components, service-life is generally expected to fall within the range of 20, 30, or even 40 years. If we consider each product generation to be a mass-market testing prototype, it is easy to see why mobile phones have exponentially increased their involvement in our everyday life over the last 10 or 15 years, by radically changing their functionality, while façades today look quite similar to how they did 80 or 100 years ago, even though their performance and functionality have vastly improved.

New methods for product development and implementation are required, closer to those of the automotive and electronics industries, if we expect to shorten the rate at which upcoming technologies are launched into the market, tested, upgraded, improved, and replaced. Since façades are massive assemblies, hardly comparable to an automobile or a smartphone in terms of material use and replaceability, a possible approach would be to fragment the façade assembly into smaller, more manageable pieces, which can be constantly and individually reassessed with the introduction of new, more effective technologies.

B **Risks and uncertainties to the client:** From the client's perspective, the decision to invest in energy-efficient systems also carries a significant risk. When we consider current occupation trends, especially in the case of residential real estate, we see that the average time a building owner will live in a single property is around 7 years (Gondrie et al., 2015). This is considerably shorter than the average time required for the return on investment of an energy-saving system. For example: photovoltaic (PV) solar panels are calculated to reach socket parity when the return on investment is equal to or higher than 5%, depending on the system's efficiency and the rate of inflation of energy prices (Bazilian et al., 2013). It is also a risk choosing the right moment to make a capital investment on sustainable technologies. Going back to the example of PV panels: the cost of a PV installation per Watt output has dropped by an average of 21% per year over the last 30 years (Mayer, Simon, Philipps, Schlegl, & Senkpiel, 2015). This means the capital investment required to buy such systems before they reach maturity - or mass-production scale - could negatively offset the return on investment of the system from energy savings due to a faster relative depreciation.

2.3 Solutions to transform the construction process

Innovation in building technologies, and especially energy-saving systems, has been accelerating at an unprecedented rate. Residential Zero-Energy renovations, which until recently represented an expensive, experimental concept, can now be realised for a relatively small additional investment of between 20% and 25% (Azcárate-Aguerre, Konstantinou, et al., 2017). However, as we have discussed before, the market-wide implementation of these systems, whether in new construction or in deep renovations, is significantly slowed by organisational and information-exchange bottlenecks in the construction industry.

This tendency can be counteracted through innovative business models that consider the accelerating rate of innovation in the supply industry, and reconciles it with the long-term financial commitment these systems represent for real estate demand interests. New products, released at shortening intervals, cannot be integrated into the market through traditional supply mechanisms. Innovative products and services demand innovative business practices and a deep industrial reorganisation (Van Nederveen & Gielingh, 2009; Vrijhoef, 2011).

Design, Build, Finance, Maintain, and Operate (DBFMO) contracts are a promising step in the direction of re-assigning long-term decision-making powers to a party (in this case a general contractor backed by a multidisciplinary consortium) with sufficient technical understanding of the construction and operation process (Straub, Prins, & Hansen, 2012). In such contracts, the centralised contractor in charge of developing and managing the building over a 40- or 50-year contract period, would have the level of responsibility and control needed to demand deep structural changes from product and service suppliers. However, as we will discuss further, DBFMO contracts are only partly successful as a Circular Economy implementation mechanism.

2.3.1 Product-Service Systems as an industry-transforming strategy - The business and supply solution

Product-Service Systems are a Business-to-Consumer (B2C) strategic model that fits within the frame of a Circular Economy structure. A PSS business model replaces a traditional purchasing scheme, in which a supplier transfers ownership and responsibility of an asset to a buyer, maintaining only limited liabilities over it in the form of technical guarantees. From a PSS perspective, the product on its own does not hold the final value, but is merely a mechanism through which a service can be delivered to a client (T. Baines & H. Lightfoot, 2013). To put this into an example involving PV cells: a traditional purchasing method would have a client buy the PV cells from a manufacturer, through a one-time cash payment or through a financial lease. The client would then own the panels, in many cases pay an additional fee for any required maintenance, suffer the technology's capital depreciation, and deal with the product's end-of-service scenario. In exchange for this he would generally get a return-on-investment from the energy savings in his property's operating costs. In a PSS model, on the other hand, the physical PV panels are not the item being sold, but are instead combined with the continual service delivered by those panels - through a long-term contract with the client or end-user - and charged relatively to their actual performance. In such a scenario, the client would not pay for (nor ever legally own) the PV panels, but would instead pay a fixed monthly or yearly amount based on the effective operation of the system, or even a variable amount related to the system's output (eg. Euro per Watts generated in a given month). The client is therefore paying not for the materials embedded in the PV panels, but for the performance provided by these to produce passive energy through the building's envelope. Product-Service Systems act, therefore, as a de-materialisation strategy. They remove financial incentives from the sale of physical products, and force manufacturers and service providers to optimise their service-delivery by minimising their use of material and human resources (T. Baines & H. Lightfoot, 2013).

From an industry perspective, this offers a number of advantages and a huge field for the development of new business structures to organise and manage a long-term, ongoing relation between suppliers of technologies (Original Equipment Manufacturers - OEMs), contractors in charge of delivering product-service packages, building owners, and end-users. In fact, PSS thinking is already being applied for individual components with an external interface with the building (meaning they are not embedded into the construction, nor interconnected with other components, and can therefore be installed/uninstalled with a relatively small effort). An example of this is the combination of products and financial/technical services offered by photovoltaic-leasing companies in the United States and the Netherlands (Liu, O'Rear, Tyner, & Pekny, 2014).

A more ambitious approach to PSS implementation would not only deal with the way in which technological systems and financial/legal contracts are packaged and sold to the end user. An integral PSS approach would completely redefine the way in which systems are designed to interact with each other by, for example, increasing standardisation and reducing compatibility issues. It would also restructure the supply chain in terms of contractual obligations. OEM suppliers would hold a long-term contract with the general contractor, who is, in turn, contracted in the long-term to deliver an optimal performance to the client. Lastly, it would promote a new form of design which facilitates replacement, upgrade, and reprocessing of obsolete components within a larger system, while guaranteeing that removed parts can be easily reused or recycled for new purposes in an expanding second-hand market.

2.3.2 Integrated Façades - The technological solution

Integrated Façades are complex building assemblies in which a large part of the building's service and climate-control systems are contained within the modular construct of the building's envelope. Integrated façade principles can be found in both curtain wall designs, as well as in self-standing modular window boxes (Klein, 2013). In most cases, a wide frame surrounding the glass façade surface will contain diverse technical systems such as: Cooling and heating, ventilation, heat-exchange, shading, energy generation and/or storage, media projection, electric and water supply, and performance-monitoring sensors.

For certain building typologies, such as cell offices, integrated façade systems can virtually eliminate the need for centralised building services which results, from a PSS perspective, in two major advantages: 1) it combines two of the four basic building elements (Structure, Envelope, Building Services, and Building Infill) into one; and 2) it facilitates the distributed functioning of envelope-integrated services according to room occupation trends, thereby avoiding the negative centralised-system effect in which large sections of the building are conditioned even when not in use.

Combining the Envelope and Building Services elements of a construction is a logical step, when we consider how closely related they are in terms of expected service-lives. While the structure of a building is generally expected to last for 50, 100, or 200 years and the interior finishes and mobiliary can be changed as often as every 5 or 10 years, building services generally provide a technical service-life within the range of 15 to 20 years. Envelopes are expected to perform for between 20 and 40 years. Combining these systems on the outside of the building can facilitate and coordinate renovation and system-replacement processes in terms of both logistics and use of materials.

TOC

Concentrating climate-control mechanisms in the façade also means the envelope will play a more determinant role than ever before in the efficient climatic and energy performance of the building, which can be an advantage when defining utilities-inclusive contracts. A Product-Service System approach to the design, installation, and operation of integrated façade modules (see Figure 2.2) would allow a service-provider to estimate, within a reasonable range, the impact of his modular products on a specific building's indoor climate and energy consumption, therefore allowing him to offer a long-term, performance-based contract, as opposed to a single outright-purchase option. It is important to note that the effect of façade and building services on climatic and energetic performance can vary according to diverse building types. It is, however, beyond the scope of this paper to analyse the extent to which a façade service provider can guarantee a determined indoor comfort level.

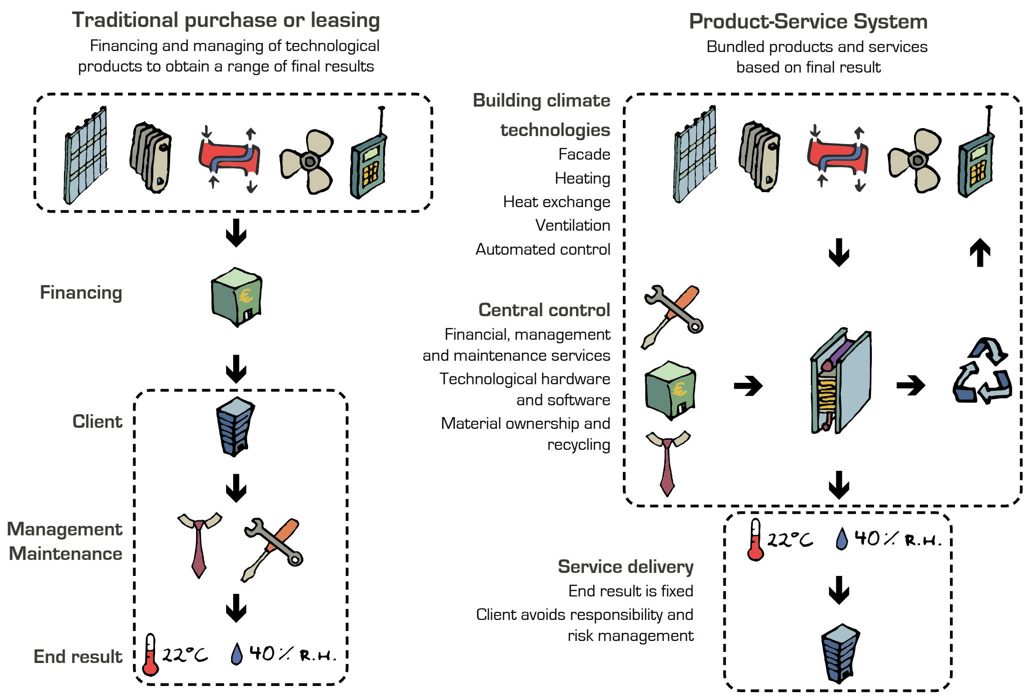

FIG. 2.2 Schematic shift from a traditional Product-System to a circular Product-Service System for integrated façades (Azcárate-Aguerre, 2014)

2.3.3 The potential of PSS for the implementation of a Circular Economy

The potential of Product-Service Systems for the implementation of a Circular Economy model lies in the correct distribution of ownership, responsibilities, and interests throughout the supply chain (Joustra et al., 2013). Under the current business structure, producers and installers of technological systems and building components are only tied to their products by a legal mechanism based on guarantees and liabilities. Such a system "punishes" the under-performance of a product, instead of "rewarding" its over-performance, see Figure 2.3.

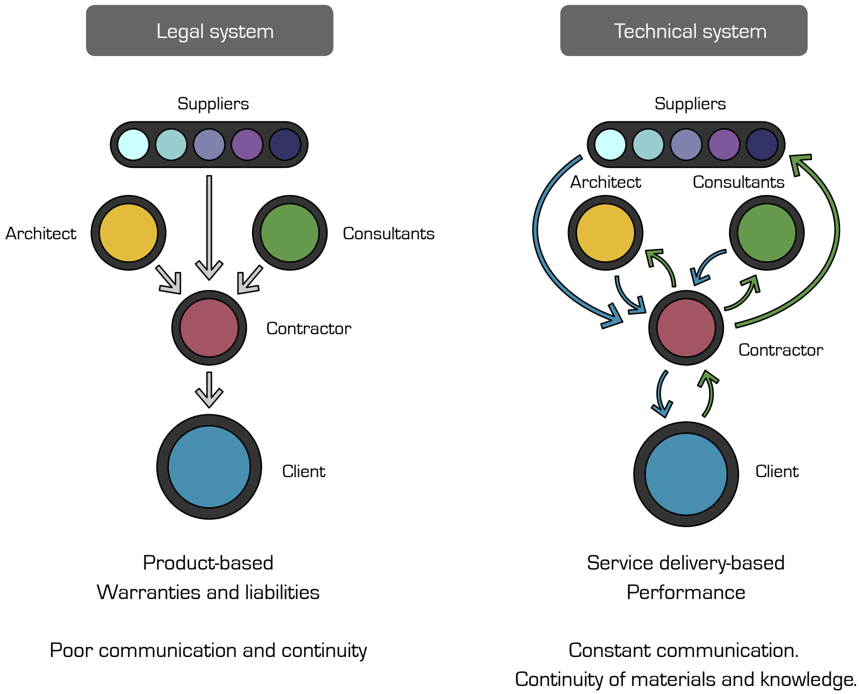

FIG. 2.3 Schematic linear vs. circular supply-chain structure, from "punishment" to "reward". (Azcárate-Aguerre, 2014)

A linear supply chain (the one currently dominating the Architecture, Engineering, and Construction industry) will have each step of the supply mechanism surrendering ownership of the physical products to the next, in exchange for a certain degree of technical guarantees. All systems are ultimately transferred to the client (by definition, in most cases, the party with the most limited technical knowledge), who then has to hire a team of facility management experts to extract the best possible performance out of these systems. Long-term efficiency, apart from major faults which would have to be covered by guarantees, are not in the interest of suppliers and manufacturers, as they no longer maintain financial ties or incentives to this performance.

End-of-Service scenarios are also negatively affected by this business structure; the client, and owner of the materials contained in the building, will frequently surrender ownership of these materials to the company in charge of demolition as a form of payment. The materials will then be extracted with varying degrees of effectiveness, and the output sold in the global market. Processing and logistic costs are high, as components are not originally designed for disassembly, making their separation process difficult and inefficient. Their sale on a global market reduces the chances that these materials will be re-used locally, thus increasing transportation expenses and related CO_2 emissions.

An intermediate business model would have a driving stakeholder - on the supplier side - being responsible for the construction and operation of the building over a determined period of time. In DBFMO contracts, for example, the general contractor in charge of the project's 30- to 50-year service-life will retain responsibility over the effective performance of the building and its systems, he will then rent the building to the client for a fixed yearly fee. DBFMO contracts do not, however, strictly follow the principles of PSS thinking, and are instead a form of extended financial lease. The contractor is effectively the constant manager of the building, and is in charge of the financing and maintenance of all components, but these contracts often do not include utility costs (meaning the contractor cannot draw direct incentives from the energy-efficiency of the building, and instead is only penalised if the performance is below a specified benchmark) and they do not specify a strategy for dealing with the building's materials at the end of the contracted period. At that point in time the client might simply become a traditional owner/manager of the building, or it might be sold in the market, or rented out in a new lease contract. The end-of-service scenario for the construction materials is therefore equally uncertain, as demolition and recycling are generally not included as part of the original planning and contracting process.

A true PSS-oriented business model will have all stakeholders tied, materially and financially, to the optimum performance of the building throughout its service life, including end-of-service material extraction and reuse. This is, however, not in the form of penalties for below-expected performance, as in the case of an operating lease, but in the form of incentives for above-expected results. A PSS method for the installation of integrated façades would include utility costs from climate control.

The Product-Service System would use the integrated façade modules as a product to deliver a final indoor comfort and energy performance as a service. This means PSS façades can become a method of Energy Performance Contracting (EPC) in which the cost of a façade renovation, through leased components, can be partially or totally repaid through the savings resulting from their increased energy efficiency. The continuous nature of the Service-Provider's role throughout the components' service lives, and the fact that an improved energy performance will result in direct profit increase, means it will be in his primary interest to maintain an optimal overall building performance through the use of updated technologies.

2.4 Conclusions

In theory, integrated façades as Product-Service Systems have the potential to permanently bridge the technical, financial, and legal knowledge gap between producers of building technologies, builders, managers, and clients. By treating each building project as an ongoing service (which may last decades or even centuries) instead of as a delivered product, a PSS can not only integrate a Circular Economy mindset into the construction industry, but also set up the business mechanisms that will ensure all parties in a project are committed, in the long term, to a single goal: the best possible functional performance of a building with the most effective, minimum use of resources. However, this transition requires changes in the innovation process, which starts with persuading stakeholders to explore the advantages, and weigh these advantages against the uncertainties and risks. Conclusions about the required PSS characteristics and conditions – the PSS brief – are summarised below.

The following section presents our arguments, from a multi-stakeholder perspective, on how this transition towards a service-oriented industry can be achieved (2.4.1 Changing roles in the innovation process), and why this transition is in the interest of the principal parties involved (2.4.2 Added value of PSS for stakeholders). It then discusses the state of research, and proposes a series of future steps necessary to bring this concept closer to its practical realisation (2.4.3 Following steps).

2.4.1 Changing roles in the innovation process

Successful radical innovation requires a major crisis or market opportunity. If the construction industry wants to develop into a market with more innovative capabilities, the innovation process has to change as well (Bers, Dismukes, Miller, & Dubrovensky, 2009; Joustra et al., 2013; Vrijhoef, 2011).

Such an industry-wide shift will not be reached without a fair amount of restructuring and collateral damage. The financial demands and long-term stability required by a long-term ongoing project could, ultimately, be unfeasible to many smaller players in the supply chain (such as subcontractors or system providers), who might have to expand and merge their businesses, or sacrifice profit under pressure from larger players further up the supply chain. General contractors will have to plan their future operations based on how many buildings they can afford to manage at any given time, while ensuring they maintain a diverse enough portfolio, instead of the current model based on delivery dates and a constant search for new contracts. This represents a major shift in the traditional business practices of such companies. The cost and risk of this transition could have a negative effect on a number of organisations and stakeholders, but could be rewarded with a greater financial stability and improved solidity to face economic fluctuations or crises.

A **The financial sector** needs to stimulate and support changes in supply and demand business models by applying new financing mechanisms. Recent studies by large banks (ABN AMRO, 2014; ING Economics Department, 2015) already show that they are exploring more innovative technical/financial packages to support new business models. The road for this has been set by relatively simpler contracting methods employed by other industries, with mobile phones and cars being among the most common. Such industries have certain advantages in this regard such as, to name but a few: a longer service-based contracting track-record, higher product-service standardisation, a clearer demarcation between client and supplier roles, and standard contract termination terms. All of these contribute to lower uncertainty and hence lower risk premiums.

The construction industry, meanwhile, is entering an exploratory phase, in which such contracts and multi-stakeholder relations are being tested in custom scenarios, while standard contracts and risk management structures are still to be developed. The 2008 financial crisis will provide a useful background for this development, as large financial institutions have been forced to change their strategy and (further) diversify their investment portfolios, thereby providing leverage against the uncertainties of increasingly fluctuating economic cycles. Financial regulation on real estate investments, which is currently based on preserving overall property value through clear ownership structures, must adapt to understand and include models of collaborative service-focused ownership. Non-regulated, or improperly regulated, investment models could have a negative effect on the sustainability of the building stock if they lead to the creation of complex, deceptive, high-risk financial products such as those which triggered the 2008 global financial crisis.

B **The architectural practice** needs to re-assess the value given to unique, irregular forms and highly customised assemblies, and consider decisions based on a modular interaction between high-performance building components. This does not mean architectural design should become a secondary priority, completely restricted by the functional requirements of standardised building technologies. However, a leasable system would rely on a certain degree of modularity and interchangeability as a way of increasing the residual value of components, which would in turn have an effect in the conceptualisation and design development processes of architects and designers.

C **Building owners – and other demand-side stakeholders** will need to explore the added value of alternative business models and (re)evaluate the traditional concept of ownership. In fact, this exploration has already taken place in many organisations, under the influence of agreements to reduce the carbon footprint and ambitions to be frontrunners in innovation. Examples can be found at universities, hospitals, and financial institutions with large building portfolios (ABN AMRO, 2014; den Heijer & Teeuw, 2011; ING Economics Department, 2015; Joustra et al., 2013).

Ongoing research has found that tools to accurately compare Total Cost of Ownership for diverse investment options still need to be further developed. This is particularly evident in the case of accurate methodologies for evaluating direct and indirect operational costs in existing buildings, information which is crucial in determining the economic attractiveness of a traditional or service-based façade renovation project.

D **New generations of decision makers** have seen great advances in the concept of *use and access* above the concept of *ownership* (Rifkin, 2001). Innumerable modern assets, such as printers, phones, cars, and real estate, are now frequently leased, rented, or shared. This represents a significant cultural deviation from a traditional tendency to own a wide range of physical assets. Internet-based applications have facilitated the dissemination of “sharing-economy” models in which people within a certain region can share products or services upon demand without the need for intermediaries (apart from the internet-based application itself). These socio-cultural changes create a positive atmosphere for the growth of more complex systems of performance-based Business-to-Business (B2B) contracting in which physical components constitute a means and not an end.

The broader social and economic consequences of such disruptive models are still, however, not fully understood. A shift towards Product-Service Systems could also entail a concentration of resource ownership in the hands of companies, which could exacerbate economic polarisation trends contributing to growing wealth gaps, both locally and globally. Such systemic consequences are difficult to model and predict, and must therefore be considered and monitored throughout the development of circular business models such as the one presented in this thesis.

2.4.2 Added value of PSS for stakeholders

An additional complexity built into the construction industry is the highly significant impact this sector has on a wide range of direct and indirect stakeholders. While a poorly functioning household item will only create a problem for the user and can most likely be returned to the manufacturer for reprocessing without any major effort, a building has a permanent presence within its context over one or more human generations. This means that the stakeholders in a building are not only the supply and demand parties directly involved in its construction and operation, but also its end users, city inhabitants, regulatory bodies, infrastructure providers, and countless others. The adoption of a Circular Economy process, in the form of PSS building components, offers considerable incentives to most of the parties involved (see Figure 2.3), especially in times of economic uncertainty when preconceptions about our economic and industrial activities should be revised. The wider groups affected by processes in the industry are listed below:

A **Demand-side stakeholders** could initially benefit the most, especially now that real estate managers are more likely to focus on Total Costs of Ownership, and not only initial investment. Rising energy prices, social trends that value the aesthetics of a “brand-new” and “high-tech” appearance, and accelerating technological innovation create a substantial economic pressure, which causes buildings to depreciate at an ever-faster rate. Real estate owners and managers are more aware than ever of the value of maintaining their building portfolio in optimal conditions. Dealing with this depreciation, however, requires deep technical understanding of the systems operating within the building (more so as buildings become more complex and filled with highly-specific technologies). By outsourcing the entire life cycle of diverse building components to technical experts who have a clear understanding of them, clients can avoid the struggle and financial risks associated with managing these systems themselves. A PSS approach would provide the following advantages according to the 4-value performance criteria identified at the start of this paper, see Figure 2.4:

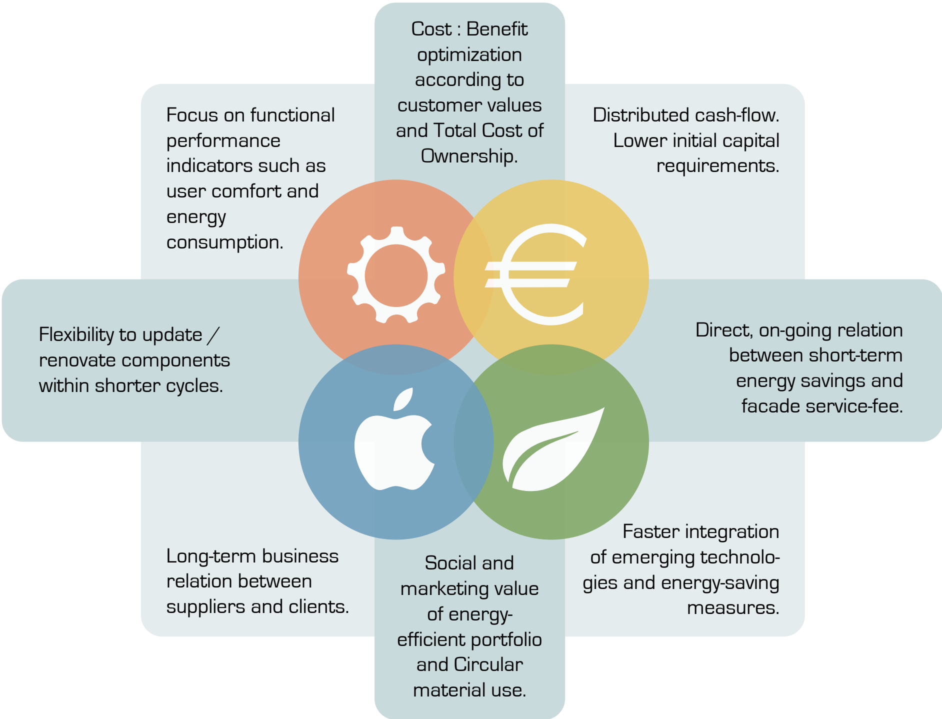

FIG. 2.4 Benefit overview of a PSS façade concept according to Den Heijer's 4-value criteria (Azcárate-Aguerre, 2014)

Sustainable/Energy: As mentioned thoroughly in this article: Sustainable, energy-performative technologies are being released into the market at accelerating rates. The strategic and financial value these technologies offer to a client institution is closely related to the use of state-of-the-art systems. Such systems can be made available and replaced (efficiently) within shorter intervals through leasing mechanisms that guarantee operational consistency and material conservation. Risks presented by lower than expected actual energy-savings, for example caused by the documented rebound effect (Guerra Santin, 2013), need to be considered, and might lead to additional monitoring and/or financial costs.

Functional: Rapidly shifting Real Estate trends demand increasing levels of flexibility in a building's architectural programme, occupancy, aesthetic design, and technical services. A service-based supply business model would significantly increase the capacity of real estate managers to respond to these changes by modifying the performance, appearance, and specifications of their building portfolio, without being weighed down by long-term investment cycles.

Strategic: The European market for commercial real estate is currently suffering from a high vacancy rate. The excessive supply of commercial floor space in certain regions forces building owners to think about additional values, which they can offer to potential clients in order to distinguish themselves from their competitors. Leasable façade systems would allow more frequent renovations and a wider functional flexibility (as stated above), which would in turn result in more attractive properties with more frequent maintenance schedules and a higher energetic performance and user comfort.

Financial: In many cases, real estate ownership and management is not the primary business activity of the client institution. Leasable products provide more equally distributed, constant cash-flows, making real estate investments more predictable and eliminating the current peaks in capital flow over a building's service life: construction, major maintenance/renovation works, and deconstruction. Outsourcing technically-demanding services, while eliminating financial peaks, would allow clients to focus resources on their primary business activities.

B **Supply-side stakeholders,** on the other hand, could exploit entirely new areas of business development. As we see with other manufacturing industries, operation and financial services are among the most profitable activities a company can engage in. Combining building components (products) with a combination of technical and financial services would thus expand the range of activities from which construction companies currently derive their revenues. Not only would it expand it but, as mentioned earlier, it would spread these revenues over a constant, steady income flow, stabilising their long-term finances and reducing their vulnerability in times of economic turmoil. This is especially relevant to the sector because, as we know, the construction industry is generally among the first and hardest hit by financial crises due to their high dependency on a small number of large, short-term projects (Cleton, 2015).

The focus on product's performance could meanwhile incentivise product innovation by shifting the focus to entire Life-Cycle engineering. Design decisions could, for example, justify higher material content or quality in exchange for longer service-lives, or lower maintenance costs. Additional investment on disassembly mechanisms could be financially justified if they lead to component or material preservation within closer economic loops of reuse, repair, and re-manufacturing. This replaces traditional recycling processes which often entail the down-cycling of valuable and critical materials due to unfeasible separation costs.

C **Regulatory bodies and society as a whole** would benefit from the more efficient use of material and financial resources resulting from keeping complex technical systems in the hands of industry experts. A circular business model, in which all parties involved in the project have a permanent interest in the correct performance of the building, would naturally lead to a more effective use of energy and raw materials (as waste of either one of them would negatively affect their business' profitability), while guaranteeing the best possible end-of-service management of all systems. Constantly involved supply-side partners would have a technical platform, and the direct incentives, to integrate new technologies more quickly into the market, making transition happen at a faster rate throughout the construction industry. Demand-side clients with more regular cash flows dedicated to covering real-estate costs would have more stability to focus on their primary processes and business objectives.

2.4.3 Following steps

This paper has established the general conceptual frame of a Product-Service System for the delivery of Façades-as-a-Service. It has set the basic parameters to be considered when designing a PSS-based business model, and formulated a value proposition from the diverse perspectives within the supply and demand sides of the construction industry. As mentioned before, many of the concepts presented in this article have been extrapolated from better documented examples belonging to other manufacturing industries which have undergone a transition towards servitisation. In order to better understand the differences of applying such models in the construction sector, our team is currently in the process of developing a pilot project and testing environment with the active participation of industry representatives from the identified stakeholder groups.

Barriers and opportunities can already be identified in the transition towards Façades-as-a-Service, and need to be further explored. One possible drawback of this system would come from the complexities of user behaviour. As seen in numerous studies, energy-based renovations frequently create a "rebound" effect, in which "Occupant behaviour has a significant effect on energy consumption, given the higher temperature settings in dwellings with insulation, mechanical ventilation and more efficient temperature control" (Guerra Santin, 2013). A possible solution for this problem would be to include a maximum-energy-use clause in the contract, specifying the range of energy consumption guaranteed by the service provider, above which the difference will be charged to the user. Another solution could be the implementation of complex monitoring systems which differentiate the building's base consumption from additional losses due to negative user behaviour.

More in-depth knowledge is also needed regarding the current process for decision-making, procurement, and contracting, which governs the building practice during the development stages. Further research will elaborate upon the value proposition offered by a PSS business model according to the project's target market, and offer alternatives as to which stakeholders within this supply chain could drive the transition to this new form of thinking. A strong focus on the demand and regulatory side will be crucial to determining further conclusions, as we believe the re-organisation of the supply industry would not be effective on its own. Instead, clients and governing bodies must clearly recognise the value these ideas hold to support their activities and interests, and be ready to undertake the structural changes necessary for their implementation.

A clearer picture of the needs and processes undertaken by owners and operators of real estate could lead to higher definition in the applicability of a PSS-based integrated façade, from a business perspective. Further research must elaborate on the conditions and incentives (established in Section 2.4 of this paper) that are required for this model to be applicable in practice. A combination of schematic technical and business prototypes must be used to develop and analyse a real-life pilot project. The objectives of this exercise must be to bring into the discussion many of the diverse stakeholders analysed, and discuss the value proposition of our model through tangible examples based on a real building case. This will facilitate a practical evaluation of the pros and cons of Façades-as-a-Service, assessed through a realistic pilot project.

Chapter conclusions

This chapter has outlined the potential economic and environmental value of a shift from Façades-as-a-Product towards Façades-as-a-Service. Faster adoption of emerging technologies, environmentally aligned business incentives, streamlining of supply-chains, and efficient allocation of knowledge and responsibility throughout a project's life-cycle are some of the key benefits identified through literature study of PSS theory and analysis of existing business models in other industrial sectors.

With many of these benefits being recognised and accepted by relevant stakeholders, the question remains: Why haven't such models been broadly implemented, or even piloted, in practice? Industry inertia or unwillingness of individuals and companies to be the "first one to try" could provide a simple explanation. This would fail to explain, however, why such models have been successfully implemented in other sectors for decades.

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3 On the use of full-scale pilot projects in this research

The chapter cites fragments previously published in the proceedings of the IEECB 2016 conference in Frankfurt, Germany, as "Azcárate-Aguerre, J.F., T. Klein and A.C. den Heijer (2016). A business-oriented roadmap towards the implementation of circular integrated façades. 9th International Conference Improving Energy Efficiency in Commercial Buildings and Smart Communities, JRC Science Hub: 463-473." It also references extracts from the technical project reports delivered to the funding organisations in the context of the described pilot projects. The "EWI" technology pilot project was described in "Azcárate-Aguerre, J. F., T. Klein and A. C. den Heijer (2016b). Integrated Façades as a Product-Service System: An innovative business model for the implementation of Circular Economies in the construction industry. Delft, Delft University of Technology". The "CiTG" pilot project was described, among other publications, in "Azcárate-Aguerre, J.F., T. Klein and A.C. den Heijer (2020). Façade Leasing Demonstrator Project: Final Business Delivery Report. Delft, Delft University of Technology."

Chapter summary

This research is, to a large extent, based on the planning, design, engineering, management, and construction process of two full-scale pilot projects implemented on two target buildings at the TU Delft campus, in the Netherlands. These are large-scale university buildings that (partly) accommodate the faculties "EWI" and "CiTG" (abbreviated as EEMCS and CEG in English, building numbers 36 and 23, see Figure 3.1 and Figure 3.2).

Full-scale pilot projects (2015-2020) have been used in this research to test not only the technological readiness of the proposed physical and digital systems, but also to explore the broader systemic questions related to management, financing, and legal structuring of a FaaS alternative. This chapter will briefly describe the two pilot projects, the open questions they set out to answer, and the (preliminary) conclusions that could be derived from them. Chapters 4 to 7 will expand on these conclusions by referencing publications on the different aspects of the FaaS systemic innovation and the current hurdles to implementation.

FIG. 3.1 TU Delft EWI Faculty Building (lowrise and highrise). (Photo: Azcárate-Aguerre, 2023)

FIG. 3.2 TU Delft CiTG Faculty Building during the FaaS Retrofit. (Photo: Juan Azcárate-Aguerre, 2019)

3.1 Introduction

Within the context of the Circular Economy transition, and the importance of renovating the building stock to allow for a more efficient use of cleaner energy, Product-Service Systems have been recognised as a promising industrial and business strategy to re-incentivise the real estate and construction sectors towards different decision-making. Access to reliable information and references on the implementation of Product-Service Systems, however, was (and continues to be) limited in either scientific depth and rigour, relevance and transferability to the built environment, or transparency in terms of real practical and commercial drivers and barriers.

In 2014, at the time this research started, several Product-Service System alternatives existed applied to the built environment. Among these can be mentioned elevators (mobility), carpeting, and lighting. Specific information about these cases, the commercial, technical, and legal basis for them, and the rate of success in terms of Circular Economy objectives, were impossible to find. Due to the commercially sensitive nature of the information, and the competitive and branding advantage such alternatives provided to their supplying companies, most available information was limited to anecdotal results, superficial motivations, and commercial advertisement.

Full-scale pilot prototype projects emerged as the only path for developing specific and detailed information on the implementability of PSS in the case of building envelopes in The Netherlands. These prototypes would provide access to direct and detailed information on the stakeholders which should be involved, the incentives and challenges they would face, and the systemic constraints that could either enable PSS implementation or render it unfeasible.

The following chapter describes the process for selecting, developing, and building the FaaS prototypes.

3.2 The TU Delft EWI Facades-as-a-Service technology pilot project

FIG. 3.3 Building complex of the EWI Faculty, TU Delft (left). Diagram showing location of the IFPSS pilot project on the north face of the complex's low-rise (right). (Photos: Azcárate-Aguerre, 2016)

The 68.000m^2 building of the Faculty of Electrical Engineering, Mathematics & Computer Science (hereby EWI after its Dutch acronym) is an iconic structure from the 1960's located at the TU Delft campus, see Figure 3.3. The building was innovative for its time, having the first double-skin façade in The Netherlands. In 2015, when the research consortia approached TU Delft's Campus Real Estate to propose a pilot project to test the FaaS concept, the building's future scenarios were being explored as a result of several technical shortcoming involving building service failures, substandard user comfort performance, and fire-safety concerns.

3.2.1 Pilot project premise and research questions

The TU Delft EWI FaaS pilot project aimed to test the technological readiness of façade and façade-integrated technologies to provide the holistic technical performance requirements of a target building. As described in (Azcárate-Aguerre, Klein et al. 2016):

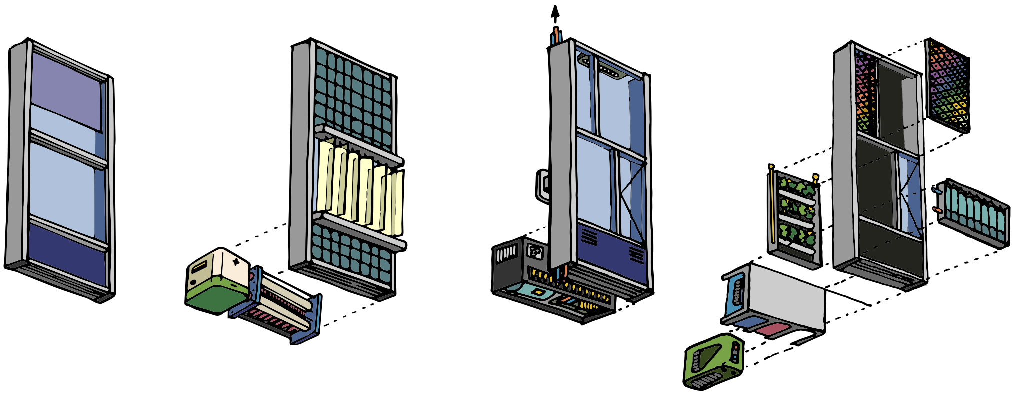
Performance contracting for multifunctional, integrated building envelopes

The evolution from a linear to a circular industry relies on significant structural changes on two fronts: On one side, it requires the *technical development of product-service combinations which will create a long-term relation between supplier and client*; on the other hand, it demands a fundamental shift in business and management processes which will facilitate the administrative, financial and logistic application of such performance-based contracts.

Integrated façades as a service-delivery tool

Products leased under a performance-based agreement should deliver a certain set of capabilities or performances to the client. The more critical these processes are to the client's activities (and the more accurately they can be measured) the higher the value held by the product-service combination (T. Baines & H. Lightfoot, 2013). Traditional façades, while performing an important number of services to a construction—such as protection against climate, noise and pollutants, ventilation, humidity control, fire safety and others—do not effectually deliver a concrete and measurable performance, as they are only part of a larger system of services and installations which control the indoor climate of the building.

Integrated multi-functional façades, which support a number of decentralised services, can expand the function of the building envelope and in certain cases encase virtually all systems responsible for the building's indoor comfort. This is especially true since certain constants such as spatial distribution, architectural design, orientation, user behaviour and others cannot be radically altered within an existing building environment without redesigning the entire structure. Integrated façades can therefore replace centralised systems such as ventilation, humidity control, heating, cooling, energy production and storage, lighting, electric and ICT supply lines, etc., and are constantly expanding the range and effectiveness of their offerings (Klein, 2013; Mach, 2015), see Figure 3.4.



1. Basic Functions
Structural
Illumination
Heat Protection
Noise Protection
Humidity Protection
Fire Protection
Overvoltage Protection
Fresh Air Supply
Glare Protection
Visual Communication

2. Energetic Functions
Solar Thermal
Photovoltaic
Energy Storage
Heat Exchange

3. Supply Functions
Mechanical Ventilation
Heating
Cooling
(De)Humidification
Electricity
Artificial Lighting
Communication

4. Advanced / Profit-generating Functions
LED (Media Projection)
Green facade (Passive Air Purification)
Green facade (Food or algae production)
Monitoring Systems
Adaptable facades (eg. U-Value)

FIG. 3.4 Service-oriented façade-integrated product combinations for multi-functional building envelopes (Image: Azcárate-Aguerre, 2015)

This means integrated façades can function as a consolidated system (envelope modules including a series of functional products and services, see Figure 3.4) that delivers a final, measurable performance (indoor quality, illumination and energy balance) to support a building's operation. This in turn enables them to become part of a Product-Service System (PSS) package in which the manufacturer, or facade fabricator, acquires a series of components from sub-suppliers, and assembles them into a complete functional product through which can be delivered a constant performance to the client through installation, maintenance, replacement and removal / reprocessing of components.

A number of integrated facade concepts have been presented, as prototypes, by teams of leading suppliers and fabricators, and their performance has been analysed in studies such as (Van Diepen, 2014). Alcoa's "Next Active Façade, Schüco's "E2 Façade" and Wicona's "TEmotion Façade" are examples of functioning integrated envelope concepts which offer diverse degrees of service-delivery potential. The fact that none of these systems has managed to generate a considerable impact in the construction industry could be attributed to the traditional, linear business model

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through which they are being offered to clients. With a higher cost per square metre and a higher degree of technical complexity (regarded as a higher risk of possible failure) clients have not yet identified the value of decentralised facade concepts, while the perceived design limitations of such modular systems results in them being unattractive to architects who might therefore be reluctant to include them in their designs.

The research question to be answered by the planning, construction, and monitoring process of the EWI FaaS pilot project was:

- **Are decentralised, façade-integrated technologies – and the planning, construction, and management processes behind them – presently capable of delivering the technological solution to the servitisation of the façade industry?**

3.2.2 EWI FaaS pilot project planning, design, and construction

The EWI pilot project engaged the collaboration of a large consortium of companies from the Dutch façade industry. All of them interested in exploring their future possible changing role in a circular, servitised construction economy. The planning process emulated a full-scale procurement process by involving the companies in an open co-creation process. It explored how physical technical systems could be integrated in the small selected target area of the EWI building's façade, and how digital asset management technologies could contribute to their effective and energy-efficient operation. This co-creation process is described in (Azcárate-Aguerre, Klein et al. 2016):

The circular business potential of product-service systems

As in the case of a Design, Build, Finance, Maintain and Operate (DBFMO) contract, the project is undertaken by a consortium made up of contractors, subcontractors and system suppliers, supported by experienced engineering, legal and financial advisors. For this project a consortium was created and divided into three main groups, with the intention of simulating the supply chain and information flow in an actual construction project. Information exchange and evaluation links have been created to reproduce the transition from a short-term project-delivery-based to a long-term service-based collaboration. The three teams can be broadly described as: Project Management team: The core team of the "Integrated Façades as a PSS" project acted as a centralised consultant, translating the functional needs of the demand parties into technical packages from the supply partners. Supply Team:

A coordination team composed of VMRG / AluEco and facade fabricator Alkondor will overview the executive design, supply chain and construction process. Demand Team: The demand team is divided into Client organisation—TU Delft's Facilities Management and Real Estate group (FMVG in Dutch)—and End-users (facilities managers, members and decision-makers of the EWI faculty). The End-user group will provide input on the current problems of the EWI building, especially with regards to indoor comfort.

Design and engineering process

A series of discussion meetings and workshops were organised with supply and demand stakeholders to identify key design aspects such as building requirements, integral product packages, current service offerings and risks and potentials of long-term collaboration. FMVG, the real estate and facilities management group of TU Delft, offered the building of the EWI faculty as a testing ground to develop a physical pilot project.

The EWI (faculty) building is a modernist construction completed in the late 60's. It has a double-façade system (pioneering for its time) made up of two panes of unitary panels made primarily of glass and steel. After almost 50 years of continuous operation the building is reaching the end of its originally built-in service life: indoor comfort and air quality are below current standards, under-performing building services and installations cause high energy and maintenance costs, and the building envelope offers poor insulation and suffers constant leakages and air draughts. The facilities management organisation has calculated that, per square metre , yearly expenses in maintenance and operation costs for the EWI building are as high as twice those attributed to their newer, comparable buildings [9]. A significant portion of these expenses can be attributed to the performance of the façade, as the poor energetic performance of the envelope results in a particularly high demand for thermal energy, and the age of the façade components require a specific and labour-intensive maintenance schedule. The building offers an ideal experimentation site due to its modular, unitised construction, while it represents a huge portfolio of university buildings constructed in the decades of the 1960's and 1970's, and which constitute a large potential renovation market of millions of square metres in the Netherlands and tens of millions across Europe (den Heijer, 2011).

The supplier consortium, coordinated by our academic team and VMRG's project development team, committed to engineering a series of four panels which would reflect the state-of-the-art in building envelope and façade-integrated technologies, to replace a section of the original façade and test its effect on the overall performance of the building. Sequenced from left to right (see Figure 3.4), these four panels (made of interchangeable modular components) would address a variety of functional requirements and levels of desired investment. The design of these panels followed a sequence in the number and complexity of services delivered and the intended length of the contract, starting with a simple “Low-cost Panel 1”, intended to extend the service-life of the building for an additional ten to fifteen years before a more extensive renovation, followed by a “Supply services and energy generation Panel 2”, (Figure 3.5) intended to support or replace centralised building services, and finally “High-end Panels 3 and 4” intended to showcase advanced systems and technologies such as self-supporting vegetation panels, LED media screens, high-wind-velocity solar shading, among others.

The interchangeability of components was a dominating topic throughout the engineering process. Looking at the building envelope as a platform for the integration of distinct (and constantly evolving) technologies, we aimed to facilitate an ongoing vitalization process, converting the building into a flexible, adaptable core structure capable of housing a diversity of users and activities over time (Wim Gielingh & van Nederveen, 2010).

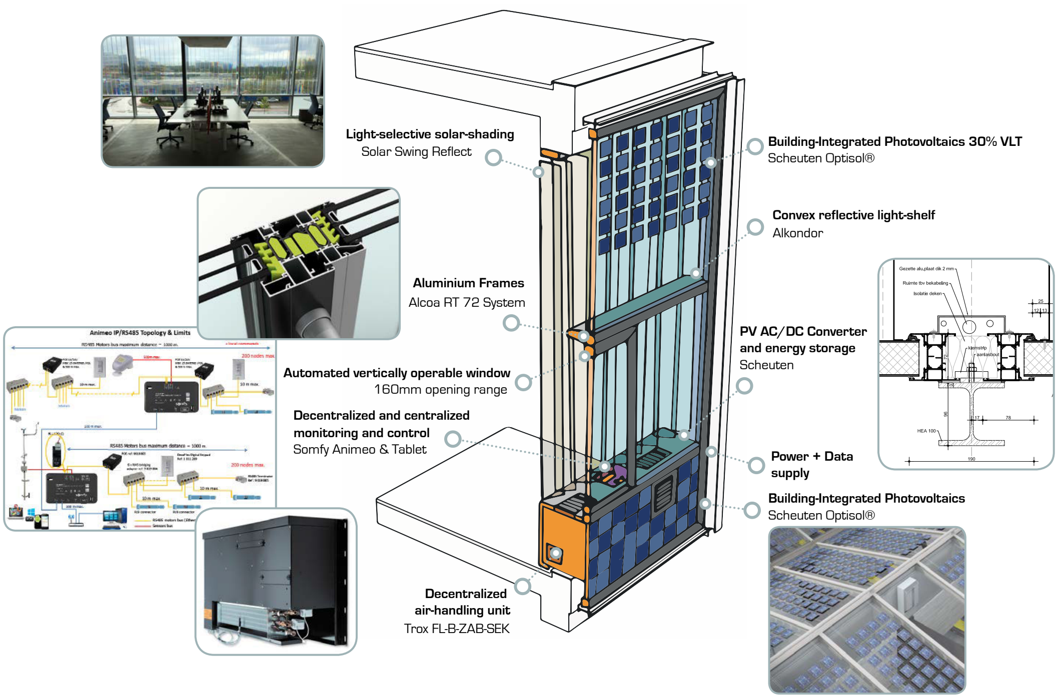

FIG. 3.5 Sketch of integrated Panel B, including energy generation and storage technologies, decentralised air-handling systems and automated window operation (Image: Azcárate-Aguerre, 2015)

The EWI FaaS technology prototype was intended mostly as a display of the types of façade-integrated technologies available at the time of construction. Some technologies which were originally planned, such as an automated self-watering green façade panel and an LED media screen, were not installed on the prototype because the technology was not yet market ready, in the case of the former, or due to concerns regarding content generation and management, in the case of the latter. Being installed on a single meeting room with a common indoor environment, the façade panels were also not meant as a laboratory installation for the purpose of measuring performance.

Parallel to the development and execution of the four installed display façade modules, a study was performed to assess the energetic and life-cycle cost performance of engineered façade packages with increasing levels of performance-delivery potential. The systems used in the evaluation were the same applied to the built prototype, and information for the study was provided directly by the supplier consortium. The technologies implemented in each package is described below, in Table 3.1.

TABLE 3.1 Breakdown of technologies used in the incremental EWI façade packages assessed for energy and life-cycle cost performance.

Evaluated technology packages		Building component	Added functionality
Central Ventilation		Trox Centralized Ventilation System	Replacement of existing centralized ventilation system at the end of its service life.
All-inclusive	**Base**	Alcoa RT72 Hi+ framing	Insulated façade structural support
		Scheuten Isolide Superplus G	Insulated double glazing
		Aluminium sandwhich panel	Insulated opaque panelling
	Base +	Renson AR75 Ventilation grill	Passive ventilation, manually operated or automated (IoT package.)
		Renson TopFix Interior Shading with Polyesterdoek Soltis® 92 screen	Automated interior shading, manually operated or automated (IoT package.)
	BiPV	Scheuten Optisol Building integrated Photovoltaics (BiPV)	In-glass electricity generation.
	IoT	Somfy Automated Control System and project-specific control algorithm.	Objective indoor-comfort monitoring. Responsive algorithmic control of installed techhologies. Connection to Building Management System.
	DV	Tro FL-B-ZAB-SEK Decentralised, façade-integrated air-management system	Decentralised air-management including ventilation, air-filtering, and (limited) heating and cooling.

Due to the time and cost limitations of the project the components used where off-the-shelf systems already designed and engineered by the participating consortium. Pro-active circularity strategies such as design for disassembly and design for adaptability could not be implemented. The life-cycle cost analysis therefore limited the effect of circular treatment of components and materials to what could be realistically estimated at the time: Cost of replacement of individual modular sub-components, whenever possible, and the residual value of materials calculated at scrap recyclable material prices at the time of evaluation. The potential value of circular regenerative construction practices could further support the case for "façade leasing" or FaaS, but realising this value recovery requires years of collaboration and development from the façade industry and is beyond the scope of this study. The FaaS model intends to inspire, motivate, and incentivise such technological development, but it is at present impossible to reach conclusions regarding its potential quantitative impact.

3.2.3 TU Delft EWI FaaS pilot project evaluation and results

The main objective of the façade engineering process was to collect, through dozens of individual and collective meetings with builders, systems suppliers, and facility managers, data related to the system integration and construction process, the projected consequences of choices in terms of life-cycle costing (i.e. maintenance, replacement, avoided energy costs, etc), and the projected cost of assembly and construction.

Evaluation of the gathered data and results can be summarised into two interrelated studies, the first one on simulated energy performance, and the second on life-cycle costing. From (Azcárate-Aguerre, Klein, & Den Heijer. 2016b):

Methodology: Energy simulations and direct performance savings

Energy simulations have been made on two different models (three variations overall) using the Design Builder software package. Model Current simulates the current double facade construction, with a steel-framed outer pane with double glazing, and a wooden-framed inner pane with single glazing. Model Base and Model Base+ are both based on an Alcoa RT72 system, with HR++ double glass and an insulated aluminium panel in the bottom segment. Model Base shows the effect of a renovated facade that does not include solar shading or ventilation, while Model Base+ includes both attributes.

Calculations are made for a typical, east-facing office with a 26m2 floor area (30m2 after renovation), and with two facade panels on its external face which add up to 14.8m2 of facade. The rooms on the north and south sides, and the hallway on the west side are set to adiabatic, as they will also be heated according to the same schedule as the simulated room. The composition of the basic facade systems can be seen in the table on the left. The main assumptions and boundary conditions for the simulation are the following:

Ventilation. One particularly relevant aspect that affects energy consumption is heat loss due to ventilation. Models Current and Base both lack operable elements, so the required air exchange is obtained by mechanical ventilation systems. Since there is no specific study on the air tightness of the current envelope, a rate of 0,7 ac/h is considered as an estimation. This value simulates a leaky envelope, considering the age and quality of the current frames and the high wind pressure on the facade. Research by Han et al. (2015) estimates an error of about 12% of the total annual energy consumption with such an assumption. This value can be further reduced through a computational fluid dynamics simulation (CFD). However, for the current study, this level of accuracy is considered sufficient. The renovated model considers an air tightness factor of 0,3 ac/h.

Shading. The panels are currently equipped with operable shading systems on the outside of the inner pane. Even though these might contribute to an improvement in the indoor comfort of the building, they do not have a great influence on the energy consumption due to positioning and a suboptimal operational schedule.

Lighting. The results indicate that the energetic internal gain due to lighting affects both the heating and cooling demands. A user profile based on occupancy and lighting control is applied in the simulation, rather than considering the lights always on during working hours.

Results.

The results from the simulations were compared with the actual energy consumption of the building, according to the TU Delft's energy monitor (http://www.energymonitor.tudelft.nl). Considering that only a small office area is examined, instead of the whole building (which includes a diversity of spaces and uses) these results allow for just a rough association to the actual percentage of gas and electricity used in the past years. This can contribute to the evaluation of some parameters, keeping in mind that the goal is a qualitative more than quantitative comparison between the two different façade systems in order to understand the impact of different renovation packages on energy demand.

When compared against the existing Model Current, Model Base shows a drastic drop of almost 60% in annual energy consumption for heating after installing the new facade system, from approximately 73 kWh/m2 to 40 kWh/m2. In contrast, the cooling energy demand increases by almost 50% from the benchmark. By replacing the double-skin facade with a single facade a significant improvement in U-value and better energy performance during the winter period is achieved. However, in the summer season, the increment in solar gains results in additional demand on the cooling system. This negative effect is specific to the EWI building case, as the current double facade, despite its poor overall performance, still offers a relatively effective buffer area which reduces its heat gains in relation to other commercial buildings of the same period. The reduction in infiltration rate after renovation, normally considered an advantage, in this case exacerbates the problem by increasing the need for artificial ventilation.

This scenario comparison nicely illustrates the opportunity losses related to inadequate decision-making during the design and engineering stages of the project. Even though the savings in heating demand are significant, the additional demand in electricity (which has a higher financial value) completely offsets the savings in gas, resulting in a Total Cost of Ownership (TCO) for Model Base which is even higher than that of the current envelope.

Model Base+ illustrates the benefits of controlled passive ventilation and properly operated solar shading. Compared against the benchmark Model Current and basic renovation Model Base, we can observe a further drop in energy demand for heating, from an original 73 kWh/m2 to 11 kWh/m2, or an almost 86% reduction overall. On the other hand, the cooling energy demand is lowered from 26 kWh/m2 to 22 kWh/m2, just 15% less.

This comparison demonstrates the positive long-term effects of a higher initial investment. Even when the construction cost of Model Base+ is almost 50% higher than that for Model Base. The potential savings of this additional investment over a 35-year Life Cycle Cost Analysis, based on a projection of recent historical data showing an increase rate on energy prices of roughly 5% per year, is almost 5 times higher than the investment differential, and overall energy consumption is less than half of that provided by the Base Model.

In an industry dominated by lowest-initial-price procurement, the economic and ecological advantages of better decision-making may be overlooked, and the potential gains foregone. The shift towards demanding TCO-based solutions is slowly taking hold in certain sectors of the industry. Product-Service Systems and Performance Contracting could be effective methods to accelerate this transition, placing the responsibility for—and interest in— technically complex decisions on the source suppliers in charge of innovation.

Methodology: Life-Cycle Cost Analysis

Developing a comprehensive Life-Cycle Cost Analysis (LCCA) is the core of the project's simulation work. The LCCA is based on up-to-date financial information for products and maintenance services provided by our consortium or partner companies. The spreadsheet template (foundation for the more advanced business model evaluation described in the Future Research section in page 44) considers **all expenses related to each component** in an integrated facade panel for the EWI pilot project over a determined amount of time. The values are calculated in terms on Net Present Value (NPV) according to the macroeconomic assumptions described in the following page.

The items included in the LCCA follow the guidelines developed by (Stanford University Land and Buildings, 2005) and break down as follows:

1. Component cost. Initial investment required by the product.

2. Utilities. *Energy costs* related to component operation (W) or, in the case of components with a resultant energy performance (such as curtain wall systems) the consumption per m2 of construction according to energy simulation models as described in the previous section. *Non-energy costs* such as water and sewer services, residual waste disposal, among others.

3. Environmental impact. *Energy-related CO2* produced during the generation of electric energy or extraction of gas at the source (based on a national average for the Netherlands. *Embodied energy* of raw materials and alloys used in the production of building components.

4. Maintenance. *Preventive* refers to routine activities intended to conserve the technical or aesthetic performance of the component (eg. bi-yearly cleaning of windows, yearly replacement of filters). *Reactive* maintenance deals with the replacement of components or sub-assemblies due to breakage or failure, the average failure rate from most supplier's products is 2% per service life. *Planned* maintenance is the replacement of components or sub-assemblies due to end of service life, generally around 25 years for most products used in the EWI case. *Deferred* is an estimation of the costs related to lack of action in the current system. In other words, it is a backlog of planned maintenance which has not been fulfilled and which can lead to negative effects in current performance.

5. Service costs represent the "labour" component of the other concepts in the analysis, they can be divided into. *Installation* labour required during the initial construction or for replacement of components. *Servicing* labour required by preventive or reactive maintenance schedules.

6. End-of-service can refer to either expenses or income, according to the service provider's success at extracting residual value from his components. It can be split into: *Residual value extraction* (income) from raw materials and reusable components. *Residual service life* (income) from the re-use of entire components which retain years of technical service at end of the LCCA period, without the need for major re-manufacturing. This type of residual value is easier to recover for components which are standardized and can therefore be re-used directly in a new project. *Demolition or disassembly* costs (expense) which reflects the additional cost of removing (uninstalling) components at the end of the LCCA period or at the end of the building's service life.

Macroeconomic context

Projecting the costs of building and operating a facade over the next 35 years (in the case of this LCCA) requires a number of assumptions and estimations regarding the inflation rates over this period of resources such as products, raw materials, labour and energy. Setting all these macroeconomic parameters into the spreadsheet we can make a sensitivity study to determine to what extent the financial model behind the new business proposition could be affected by changes in the widest socioeconomic context. We can then set minimum and maximum deviation points, at which the current estimate becomes unfeasible, and a recalculation must be done to guarantee the financial health of the performance contract.

These values become crucial when determining the responsibilities and extents of the performance contract, both suppliers and clients should be protected against radical changes in economic environment or policy which could tilt the balance in favour of one or the other party. An option for recalculating the LCCA every certain number of years could be a successful strategy to guarantee that the project remains fruitful for all stakeholders involved.

Apart from the building-specific values, which will be discussed in the following section of this report, the most important assumptions made in macroeconomic context can be divided into:

Energy Data. Represents an approximation of the current cost of energy, both electric energy and gas. It also extrapolates the related CO2 impact of this energy using the average national ratio of the Netherlands. Even though the low current price of energy means that deep energy renovations are currently rarely pursued for economic reasons, but mostly for strategic or functional ones, it can be assumed based on data from the previous decades, that the trend of a roughly 5% yearly increase in energy costs will continue for the foreseeable future.

Financial Data. Includes costs related to taxes (BTW in the Netherlands), Cost of Capital (CoC) based on the expected credit rating of both suppliers and clients; expected inflation rates for diverse types of resources; and insurance costs and safety margins designed to protect the service provider against (among others) differences between simulated and real energy consumption after renovation.

Material Data. Summarizes the current market value of a series of recycled materials which are widely used in the facade construction industry. One of the main expected advantages of implementing a Product-Service System is to increase the resilience of manufacturers against changes in raw material prices (going back to the opening arguments on page 7 of this report). Even though the price of raw materials is in many cases negligible under current market conditions, analysis and forecasts done by leading consultancy groups such as (McKinsey & Co, 2013) show that in the last 15 years the price of commodities such as metals has increased by an average of 174%. As this trend is expected to continue, especially in the case of rare-earth metals and other high-value / low-volume resources, access to raw material flows will become a matter of geopolitical strategic importance. Facilitating access to these materials, and retaining ownership over them, will most likely become much more relevant in the coming years than it is perceived today.

Renovation packages - LCCA Results

As mentioned before, the LCCA study is divided into individual components according to the specifications of the EWI building pilot project. By separating the study into single components, we can easily add these blocks together into diverse packages with increasing degrees of service delivery potential. We can then evaluate their behaviour in terms of each package’s TCO (Figure 3.6).

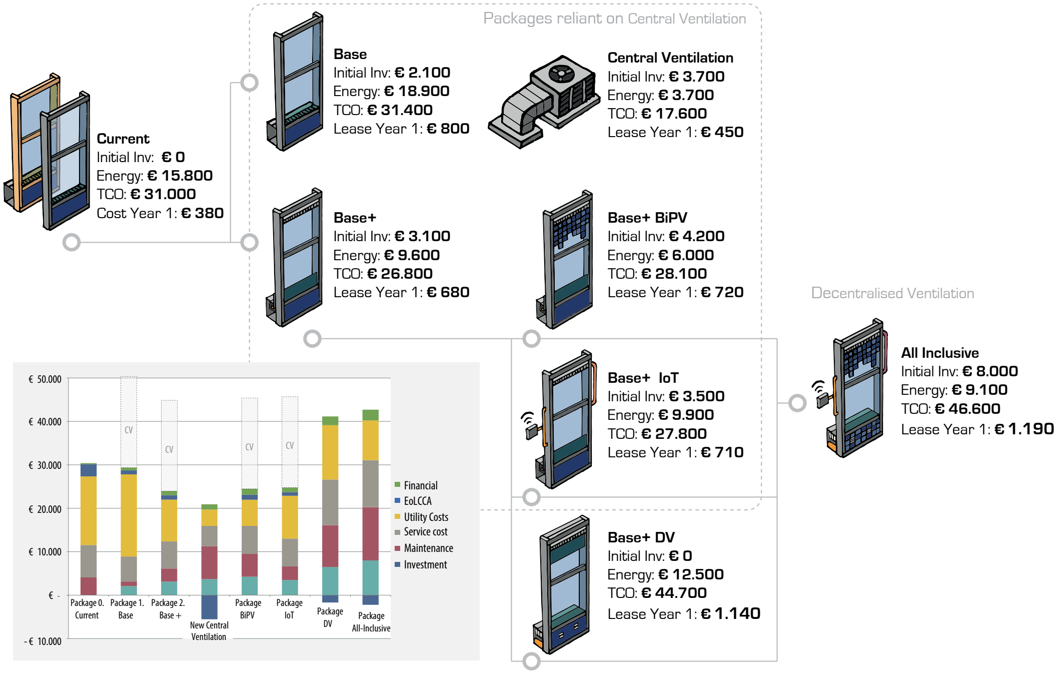

FIG. 3.6 Total Cost of Ownership comparison between the renovation packages analysed over a 35 year LCCA period.

The graph on the left shows the poor performance of the Base renovation, being very similar in cost to the current system but with a significantly worst energy performance. In terms of TCO, the All-inclusive system provides the best value for cost, as it provides most of the building's service requirements for a relatively modest additional investment.

As in the case of the energetic simulations, at this stage of the study we are looking for rough cost-to-benefit relations, and not at the precise quantitative price at which the system could be immediately leased. Further research and sensitivity analysis will be necessary, beyond the scope of this pathfinder study, to determine the precise price of each package at a market-ready stage of development. Following these criteria, we decided not to elaborate LCCA studies for the panel designs of the pilot project, which would have resulted extremely specific and difficult to compare, but instead work through a process of gradual aggregation, in which we looked at the behaviour of the system by adding individual decentralized components at each step. The main study sets are:

Current System. Facility management organizations can decide (and often do) not to renovate their building envelope, even if it is beyond its planned service life. This results in an initial investment of zero, as no new components must be added. The obsolescence of the system, however, results in rapidly increasing expenses on energy consumption, maintenance, down-time and even user productivity. One of the main reasons not to invest in a new facade tends to be the opportunity cost related to such a decision, in other words, the primary business activities on which the client organization would rather invest their resources, expecting a larger return on their investment. While opportunity costs on a purchasing scheme can be an important obstacle, they represent one of the advantages in a leasing scheme, as the resources in cash or credit to which the organization has access are not fully locked into the renovation project, but only the relatively small fee needed to pay for the leasing costs. These resources are therefore unlocked and can be used on other investments, without sacrificing the quality and currency of the facilities.

Base and Base+ packages. As described in the energy calculation section before, show the impact of short-term and long-term visions when making basic renovation decisions. Assuming the centralized ventilation installations are also outdated, and should be replaced to reach higher energy performance, we also evaluate the cost of a new *centralized ventilation system*.

In the last stage, we look at the effect of three specific technologies: *Building Integrated Photovoltaics* **(BiPV)** which can generate part of the energy required by the building, a remotely controlled platform for the operation of Ventilation and Shading using the I*nternet of Things* embedded into these components **(IoT)**, and a package with a *decentralized, facade integrated air-handling unit* **(DV)**.

Finally, the **All-Inclusive** package combines a Base+ system with all three upgrades (BiPV, IoT and DV). Even though every package offers additional insight into the cost-benefit impact of facade design decisions, the most interesting comparison is probably between the Current, the Base+ with new centralized ventilation, and the All-inclusive systems. On top of this, it will be important to study the difference between purchase and leasing schemes, and the impact this will have on the cash flow of both supply and demand organisations.

3.2.4 TU Delft EWI FaaS pilot project conclusions

The design, planning, and construction process for the EWI FaaS Technology pilot project (see Figure 3.7) spanned from Spring 2015 to Spring 2017, when the replacement of the 4 target panels was completed. The main outcome of this study will be described in detail in Chapter 4 of this thesis. Key conclusions from the pilot project development process are summarised below:

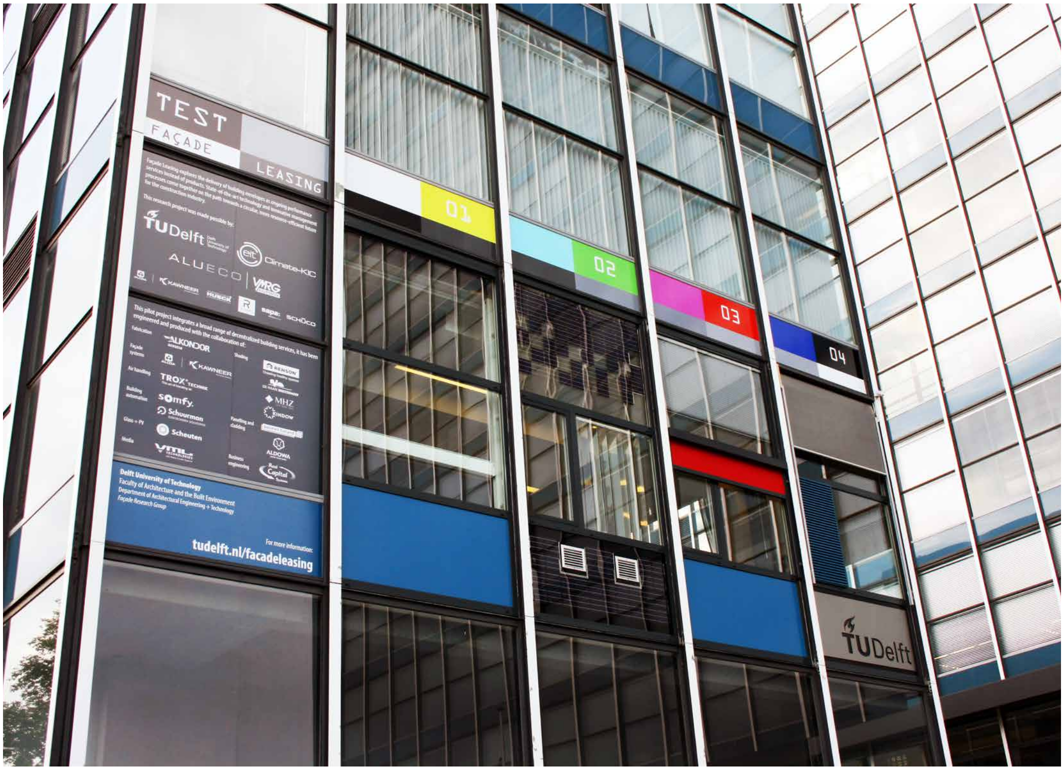

FIG. 3.7 Completed FaaS Technology pilot project at the building of the faculty of Electrical Engineering, Mathematics _ Computer Science (EWI) at TU Delft, the netherlands. (Photo: Marcel bilow, 2016)

- Technological readiness is high at an individual component level. Façade-integrated technologies are capable, in a certain range of building typologies, of de-centrally delivering the functional requirements of the target building in terms of building services, energy performance, and user comfort.

- In terms of planning and execution process, the interdisciplinary integration and supply-chain management needed to accomplish such technically complex façades is yet to be developed into an industry standard. While the façade fabricator took over most of the responsibility in terms of engineering, technology integration, and construction site management, certain demarcation problems existed during the process. This included electrical and plumbing connection, and digital calibration of the different components to the rest of the building, and to the building management system respectively.

- A decentralised integrated façade could be a technically and financially feasible option, even for legacy buildings such as the EWI, which haven't been planned from the start to use such technologies. The cost of such a façade is high, when compared against a traditional façade, but competitive when taking into account the central building services it replaces (e.g. ventilation, heating, cooling, BiPV power generation, user monitoring, et.)

- Construction of an integrated façade system is just one first step in the testing and implementation of a FaaS model for façade contracting. The technical readiness was tested and to a large extent confirmed. However, the financing, coordination, procurement process, and long-term management of the Façade-as-a-Service requires systemic multi-disciplinary solutions far beyond the scope of this pilot project.

3.3 The TU Delft CiTG Facades-as-a-Service Management pilot project

The 66.500m^2 building of the Faculty of Civil Engineering and Geosciences at TU Delft (hereby CiTG after its Dutch acronym) was built in the mid-1960's, and is located at the TU Delft campus. By the late 2010's its original façade, consisting of a painted steel frame with single glazing, manually operable windows. and internal blinds, was technically insufficient to deliver current standards of energy efficiency and comfort. Despite this technical obsolescence, and as a result of an uncertain planning horizon and future strategic decisions for the use of the building, in 2018 a minor maintenance was made of the CiTG's West façade. The maintenance consisted mainly in the cleaning and repainting of the steel profiles to prevent their future corrosion, but had no positive impact of the energy performance or indoor comfort.

3.3.1 Pilot project premise and research questions

In late 2018, before the East façade of the CiTG building received the same minor maintenance treatment as the West facade, the FaaS research team proposed to TU Delft's Campus Real Estate group to jointly evaluate a FaaS alternative for the ~2.600m^2 of the CiTG's East façade. This evaluation would go beyond the technological readiness level of the EWI pilot project, and would test the many ideas and challenges developed by the FaaS consortium up to that point in terms of long-term project financing, legal framework, and managerial processes necessary for FaaS implementation.

The evaluation of such aspects of the model would require a real-time and full-scale project development process, capable of delivering enough information and concrete questions to the multi-disciplinary team of academic and professional experts on (public) procurement, project financing, cost evaluation, building law, real estate valuation, and others.

The research question was developed:

- **Are systemic project development, financing, procurement, and management processes presently capable to adopting PSS alternatives? And can this adoption be efficiently and effectively organised under current systemic processes?**

3.3.2 EWI FaaS pilot project planning, design, and construction

Due to the large scale, budgetary and technical constraints of the building and its façade, the CiTG FaaS pilot project could not achieve the same level of technical complexity and building service integration achieved in the EWI project, see Figure 3.8. In terms of technical solution, the CiTG pilot project consisted of the replacement of the old steel facade panels with a new insulated aluminium system. HR++ double-glazing would be used, with manually-operable windows at user height, and automatically operated windows near the ceiling which would allow for night-cooling of the entire building during summer nights. An external automated sun-shading system was installed, with would also be centrally controlled to optimise indoor comfort levels. All automated technologies could be overridden by the users. The engineering process is described in (Azcárate-Aguerre, Klein et al. 2020):

FIG. 3.8 (Photo by Azcárate-Aguerre (2019))

The project included the renovation of 2600 m2 of facade area, and the preparation of legal, financial and managerial processes to enable the implementation of a FaaS model. Digital twin technology reports data related to occupant comfort and technical condition of components. FaaS, Facades-as-a-Service.

The first step towards proposing a deep energy renovation solution for the CiTG building was to understand its current performance through the use of climatic simulation software. The chair of Building Technology and Climate Responsive Design at TU Munich's Faculty of Architecture was responsible for creating this simulation model and experimenting with several technical variables such as energy performance of base facade elements (framing and glazing), presence and operation of solar shading, and presence and operation of night-cooling ventilation.

Corresponding to data gathered from user interviews, the model showed over 300 over Kelvin hours per year in the existing situation. Since most of these occur during office hours this translates into more than 30 days per year during which the building's temperature is above that which would be allowed by current indoor comfort regulations.

Improvement of the thermal performance of the base facade elements and use of internal solar shading would normally be a standard response to a building's thermal performance problems. Insulation of the building envelope does indeed reduce energy consumption by vastly reducing the demand for active heating during the winter. However, as shown by variants 1 through 3, over Kelvin hours in scenarios where only glazing and framing are improved worsen compared to the benchmark, with indoor shading doing little to solve the problem. The reason for this is that the current facade, after 50 years of operation, has considerable air leakage due to natural deterioration of the facade elements. While this would normally be undesirable, in this case it contributes to lowering the temperature of the building during the summer by providing an uncontrolled form of night-cooling.

Variables 4 and 5 show the impact of applying either external solar shading or centrally controlled night ventilation, with neither one of these solutions fully solving the over-heating problem. Variant 6 applies both solutions in combination and achieves the elimination of over-heating hours.

This study shows the importance of considering not only energy savings (as variants 1 through 3 provided a reduction of almost 80% in primary energy use) but also indoor comfort and occupant satisfaction. While it is hard to scientifically measure the drop in staff productivity resultant from an inadequate indoor comfort, the high relative cost of staff to a business or organization points towards a much higher monetary value for improving staff comfort and productivity than from simple and direct energy savings (figures on the right).

The building envelope's performance is therefore expected to decrease from a current benchmark of 214,3 kWh/m2 to a post-renovation consumption of 45,6 kWh/m2 (Table 3.2).

Based on the outcome of the climate and energy design study previously presented TU Delft AE+T and Alkondor Hengelo collaborated on the design and engineering of the facade solution. The proposed facade is based on a high-performance Schüco AWS 75 BS HI aluminium block-frame system, with insulated triple-glazing. The system achieves a U-value (or thermal transmittance coefficient) of approximately 0,8 W/m²K, an 85% improvement from the current facade which has been calculated to have a U-value of 5,4 W/m²K. A block-frame alternative has been selected as it results in more slender framing elements, closer in appearance to the current and original facade system used in the building.

TABLE 3.2 Results of the energy and indoor comfort performance calculations performed for the façade engineering alternatives according to the following scenarios: *Existing. Single glazing, steel frames*;

	Infiltration 1/h	Window	Sun protection	Night cooling	Over Kelvin hours DIN 4108	Over Kelvin hours DIN 15251	Primary energy kWh per m^2
Base case model	0.35	**Single-U** ID 122 U=5.4 g-value = 0.81	None	Deactivated	313	10	**214.3**
Variant 1	0.15	**Double-U** ID 3212 U=1.23 g-value = 0.74	None	Deactivated	1039	98	**48.7**
Variant 2	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	None	Deactivated	673	46	**42.6**
Variant 3	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**Internal fc = 0.7**	Deactivated	634	43	**42.2**
Variant 4	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**External fc = 0.13**	Deactivated	9	0	**45.8**
Variant 5	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	None	**Activated**	373	19	**42.5**
Variant 6	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**External fc = 0.13**	**Activated**	0	0	**45.6**

Variant 1. Double glass; Variant 2. Triple glass; Variant 3. Triple glass, internal blinds; Variant 4. Triple glass, external sun-shades; Variant 5. Triple glass, night ventilation; Variant 6. Triple glass, external sun-shades, night ventilation.

External solar shading is installed within the overhang of the upper floor, reducing the visual presence of the system while not in operation. An automated window at the top of each facade panel is connected to a centralized control system, allowing for simultaneous opening of all windows in order to passively ventilate the office spaces during cool summer nights. Also automated operable windows at user-height can be both de-centrally and centrally operated to permit user flexibility while also providing central management capacity to control all windows for indoor climate or building security reasons (Figure 3.9).

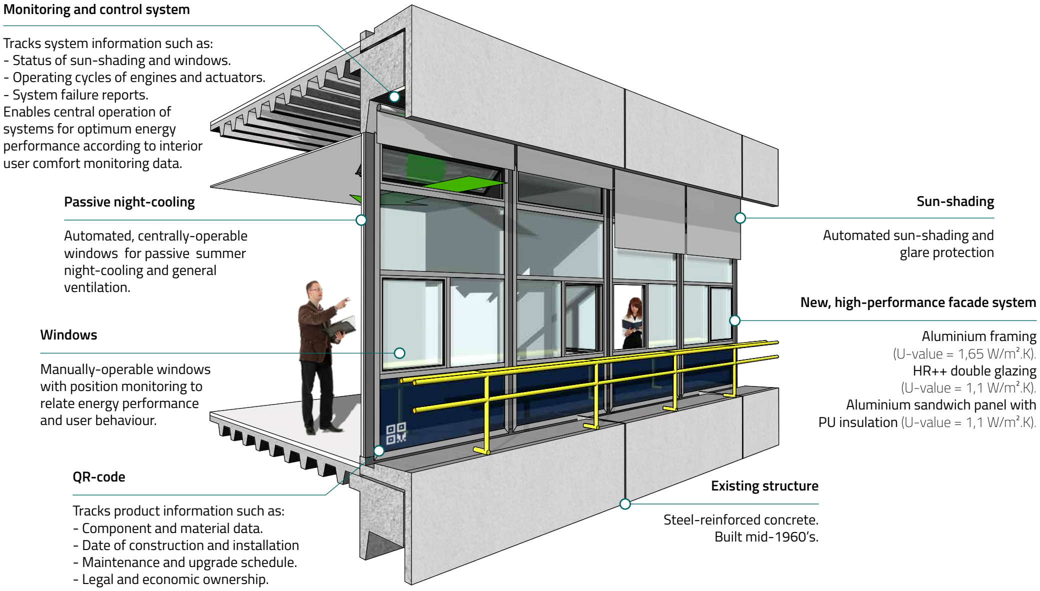

FIG. 3.9 Rendering of new CiTG Facade Leasing renovation solution, which includes high performance framing and glazing, centrally operable windows including an upper window for night-cooling airflow, and external solar shading with high-wind velocity resistance. The panels have also been designed in consultation with the original building architect to ensure its close resemblance to the original architectural appearance of the building.

Also connected to a central building management system are the engines powering solar shading systems and actuators powering operable windows. As part of the performance service delivered by the service provider is the maintenance and replacement of such systems. In the current way of working preventive maintenance is rarely enforced, automated systems are operated until an engine or actuator failure, at which point the building manager will request a facade fabricator or system supplier to replace the failing component. The cost of this is needlessly high, as individual service request are issued for each system failure and a service team must visit the building and setup maintenance infrastructure such as elevators or cranes to access the failing system. Under a performance service contract, the service provider has the incentive to monitor the operation of these systems, controlling the number of operation cycles through which engines and actuators have gone. As these components reach the end of their expected statistical service life the service provider will plan and execute a single replacement project, removing and replacing hundreds of components in one go with considerable economy of scale savings. The same economy of scale also allows for a circular reprocessing of bulk quantities of components, which can be re-manufactured for further use in the same building or another similar service contract.

In terms of management and project development processes (the actual end objective of this pilot project) the consortium started with a long-term financial Total Cost of Ownership evaluation of the project. (From Azcárate-Aguerre, Klein et al. 2020):

Total Cost of Ownership comparison – Client's perspective

A distinction is made in the study between hard, tangible costs and values, and soft, intangible values. Hard costs represent all monetary expenses which must be made throughout the study period, such as initial investment, costs of capital / financing, maintenance, cleaning, and management, and Value Added Taxes. On the hard values side could be considered energy savings according to simulated data, though monitoring throughout 2018 to 2020 will show if the expected energy-performance improvement is reached in practice. An added complexity of taking energy-savings into account is the uncertainty of energy price trends when looking into the distant 30-year future. If energy prices drop during this time, the actual financial performance of the investment, in relation to avoided energy costs, will be lower than expected. On the other hand, a sharper increase in energy prices would lead to a better-than-expected financial performance.

In terms of intangible values, the study is limited to those values which can be relatively accurately monetised, such as the productivity of employees subject to a more or less comfortable indoor environment. Various indoor comfort studies point to a figure of between 2% and 4% in employee productivity related to a comfortable indoor environment. These figures, however, are often scientifically disputed due to the difficulty of measuring productivity, particularly in office activities and spaces. The uncertainty of user productivity value or cost, and the less uncertain but still hard to determine value of energy savings have been considered in the study by separating them into an alternative graph (shown in dashed lines on the right), see Figure 3.10. This way they can be visualised and considered during the decision-making process, but not confused with the hard costs and values which can be more certainly expected during the project's service-life.

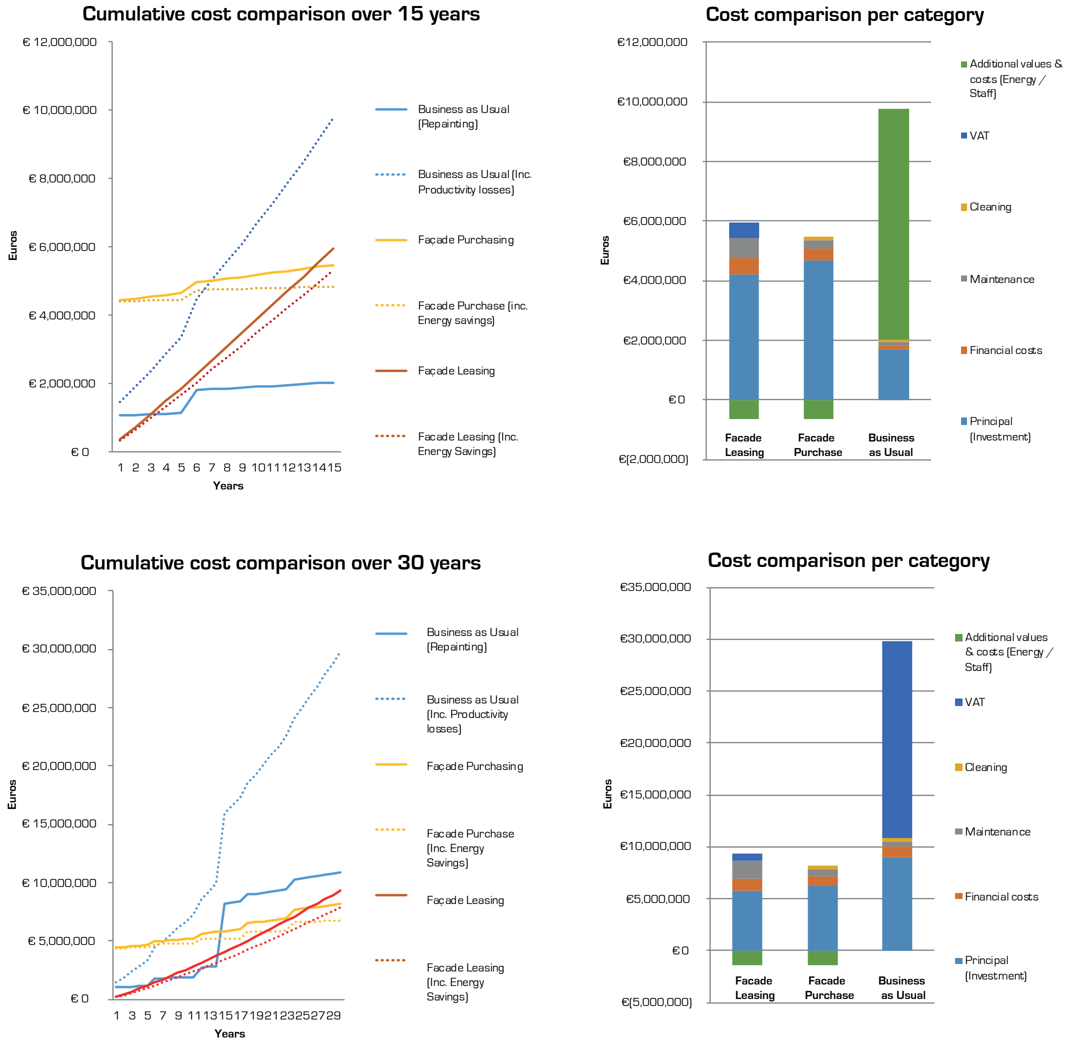

FIG. 3.10 Diverse financial graphs showing Total Cost of Ownership comparison between the three studied scenarios over a study period of 15 and 30 years.

The study can be further developed to include even more intangible sources of cost and value, for example the branding cost (for the building owner) of having an unsustainable building which is perceived as such by the general public who is ever more conscious of the importance of energy efficiency. An intangible source of value is the facade appearance, as new and better-repaired façades will give the building a higher aesthetic value that a technically outdated or ill-repaired facade. Such intangible costs and values have been excluded from this study due to the difficulty of calculating their monetary value, and the lack of approved international valuation standards to do so.

The study shows that, focusing only on tangible costs and values, facade leasing can be a solution for organisations dealing with uncertainty. As the CiTG case demonstrates, delaying a major renovation decision can have negative effects on the final financial performance of the project. This as the renovation works will need to be carried out eventually anyway, and the higher energy and maintenance costs incurred while the facade is not yet renovated which result in foregone savings during this period. Acting as early as possible is not only most likely better from a financial perspective, it is also the most sustainable alternative as we face the urgent challenge of massively updating our building stock to higher energy performance standards.

The client's perspective study was followed by a financial study from the perspective of the service provider. (From Azcárate-Aguerre, Klein et al. 2020):

Cash-flow analysis – Service provider / Special Purpose Vehicle perspective

A cash-flow analysis has been elaborated from the perspective of the Special Purpose Vehicle created to own and manage the leased façade, [see Figure 3.11]. The cash-flow analysis takes into account financial data provided by financial organisations involved in the project, such as possible interest rate on the transaction, and minimum equity investment needed as collateral to guarantee this cash-flow based financing model. The model therefore relies on a 30:70 equity to debt ratio, with an equity interest rate of 5% and a debt interest rate of 1,5%, resulting in a Weighted Average Cost of Capital of 2,05% and a potential financial cost to the Lessee of 2,5% to allow for a reasonable profit margin.

The study takes into account a residual value for the facade components of 10% at their end-of-service, as the cost of removing, cleaning, and eventually re-manufacturing these components must be taken into account before the facade can be made available in the second hand market. This residual value is, at the moment, a source of great uncertainty. First, there is currently a very limited second-hand market for pre-used façades, meaning historical data is largely unavailable to determine residual value trends. Second, it s expected that tightening regulation aimed at promoting a circular use of materials will incentivise the use of more pre-owned components (or otherwise penalise the use of virgin materials and components). If this happens a new and much larger market for second-hand components is expected to arise, but at the moment this cannot be assumed. Third, while advancement in building and facade technologies is no longer occurring at the fast rate of the post-1970's oil crisis period, and façades have reached very high levels of energy and functional performance, it is unknown how technology will change in the coming years, and what effect this might have on the value of legacy equipment built in 2019.

	Discount	Equity (Exc. Residual Value)			Debt (Bank loan)			Special Purpose Vehicle (Lessor) Cashflow							
		Principal	Interest	Payments	Principal	Interest	Payment	Income (Nominal)	Income (Real)	VAT	Expenses (Nominal)	Expenses (Real)	Balance (Nominal)	Balance (Real)	
1	1,03	€ 425.017,60	€ 21.250,88	€ **35.418,13**	€ 1.487.561,60	€ 22.313,42	€ **71.898,81**	€ **101.870,14**	€ **98.903,04**	€ 21.392,73	-€ **107.316,94**	-€ **107.316,94**	-€ 5.446,81	-€ 8.413,90	
2	1,06	€ 410.850,35	€ 20.542,52	€ **34.709,77**	€ 1.437.976,21	€ 28.759,52	€ **78.344,91**	€ **101.870,14**	€ **96.022,37**	€ 21.392,73	-€ **113.054,68**	-€ **106.564,88**	-€ 11.184,55	-€ 10.542,51	
3	1,09	€ 396.683,09	€ 19.834,15	€ **34.001,41**	€ 1.388.390,83	€ 27.767,82	€ **77.353,20**	€ **101.870,14**	€ **93.225,60**	€ 21.392,73	-€ **111.354,61**	-€ **101.905,24**	-€ 9.484,48	-€ 8.679,64	
4	1,13	€ 382.515,84	€ 19.125,79	€ **33.293,05**	€ 1.338.805,44	€ 26.776,11	€ **76.361,50**	€ **101.870,14**	€ **90.510,30**	€ 21.392,73	-€ **109.654,54**	-€ **97.426,64**	-€ 7.784,41	-€ 6.916,34	
5	1,16	€ 368.348,59	€ 18.417,43	€ **32.584,68**	€ 1.289.220,05	€ 25.784,40	€ **75.369,79**	€ **101.870,14**	€ **87.874,07**	€ 21.392,73	-€ **107.954,47**	-€ **93.122,47**	-€ 6.084,33	-€ 5.248,40	
6	1,19	€ 354.181,33	€ 17.709,07	€ **31.876,32**	€ 1.239.634,67	€ 24.792,69	€ **74.378,08**	€ **101.870,14**	€ **85.314,63**	€ 21.392,73	-€ **106.254,40**	-€ **88.986,39**	-€ 4.384,26	-€ 3.671,75	
7	1,23	€ 340.014,08	€ 17.000,70	€ **31.167,96**	€ 1.190.049,28	€ 23.800,99	€ **73.386,37**	€ **101.870,14**	€ **82.829,74**	€ 21.392,73	-€ **104.554,33**	-€ **85.012,24**	-€ 2.684,19	-€ 2.182,50	
8	1,27	€ 325.846,83	€ 16.292,34	€ **30.459,59**	€ 1.140.463,89	€ 22.809,28	€ **72.394,66**	€ **101.870,14**	€ **80.417,23**	€ 21.392,73	-€ **102.854,26**	-€ **81.194,10**	-€ 984,12	-€ 776,88	
9	1,30	€ 311.679,57	€ 15.583,98	€ **29.751,23**	€ 1.090.878,51	€ 21.817,57	€ **71.402,96**	€ **101.870,14**	€ **78.074,98**	€ 21.392,73	-€ **101.154,19**	-€ **77.526,26**	€ 715,95	€ 548,71	
10	1,34	€ 297.512,32	€ 14.875,62	€ **29.042,87**	€ 1.041.293,12	€ 20.825,86	€ **70.411,25**	€ **101.870,14**	€ **75.800,95**	€ 21.392,73	-€ **99.454,12**	-€ **74.003,20**	€ 2.416,02	€ 1.797,74	
11	1,38	€ 283.345,07	€ 14.167,25	€ **28.334,51**	€ 991.707,73	€ 19.834,15	€ **69.419,54**	€ **101.870,14**	€ **73.593,15**	€ 21.392,73	-€ **97.754,05**	-€ **70.619,60**	€ 4.116,09	€ 2.973,55	
12	1,43	€ 269.177,81	€ 13.458,89	€ **27.626,14**	€ 942.122,35	€ 18.842,45	€ **68.427,83**	€ **101.870,14**	€ **71.449,66**	€ 21.392,73	-€ **96.053,98**	-€ **67.370,33**	€ 5.816,16	€ 4.079,34	
13	1,47	€ 255.010,56	€ 12.750,53	€ **26.917,78**	€ 892.536,96	€ 17.850,74	€ **67.436,13**	€ **101.870,14**	€ **69.368,61**	€ 21.392,73	-€ **94.353,91**	-€ **64.250,42**	€ 7.516,23	€ 5.118,19	
14	1,51	€ 240.843,31	€ 12.042,17	€ **26.209,42**	€ 842.951,57	€ 16.859,03	€ **66.444,42**	€ **101.870,14**	€ **67.348,16**	€ 21.392,73	-€ **92.653,84**	-€ **61.255,10**	€ 9.216,30	€ 6.093,06	
15	1,56	€ 226.676,05	€ 11.333,80	€ **25.501,06**	€ 793.366,19	€ 15.867,32	€ **65.452,71**	€ **101.870,14**	€ **65.386,56**	€ 21.392,73	-€ **90.953,77**	-€ **58.379,76**	€ 10.916,37	€ 7.006,80	
16	1,03	€ 212.508,80	€ 10.625,44	€ **24.792,69**	€ 743.780,80	€ 14.875,62	€ **64.461,00**	€ **101.870,14**	€ **98.903,04**	€ 21.392,73	-€ **89.253,70**	-€ **86.654,07**	€ 12.616,44	€ 12.248,97	
17	1,06	€ 198.341,55	€ 9.917,08	€ **24.084,33**	€ 694.195,41	€ 13.883,91	€ **63.469,29**	€ **101.870,14**	€ **96.022,37**	€ 21.392,73	-€ **87.553,63**	-€ **82.527,69**	€ 14.316,51	€ 13.494,68	
18	1,09	€ 184.174,29	€ 9.208,71	€ **23.375,97**	€ 644.610,03	€ 12.892,20	€ **62.477,59**	€ **101.870,14**	€ **93.225,60**	€ 21.392,73	-€ **85.853,56**	-€ **78.568,16**	€ 16.016,58	€ 14.657,44	
19	1,13	€ 170.007,04	€ 8.500,35	€ **22.667,61**	€ 595.024,64	€ 11.900,49	€ **61.485,88**	€ **101.870,14**	€ **90.510,30**	€ 21.392,73	-€ **84.153,48**	-€ **74.769,28**	€ 17.716,65	€ 15.741,01	
20	1,16	€ 155.839,79	€ 7.791,99	€ **21.959,24**	€ 545.439,25	€ 10.908,79	€ **60.494,17**	€ **101.870,14**	€ **87.874,07**	€ 21.392,73	-€ **82.453,41**	-€ **71.125,04**	€ 19.416,72	€ 16.749,03	
21	1,19	€ 141.672,53	€ 7.083,63	€ **21.250,88**	€ 495.853,87	€ 9.917,08	€ **59.502,46**	€ **101.870,14**	€ **85.314,63**	€ 21.392,73	-€ **80.753,34**	-€ **67.629,65**	€ 21.116,79	€ 17.684,98	
22	1,23	€ 127.505,28	€ 6.375,26	€ **20.542,52**	€ 446.268,48	€ 8.925,37	€ **58.510,76**	€ **101.870,14**	€ **82.829,74**	€ 21.392,73	-€ **79.053,27**	-€ **64.277,55**	€ 22.816,86	€ 18.552,20	
23	1,27	€ 113.338,03	€ 5.666,90	€ **19.834,15**	€ 396.683,09	€ 7.933,66	€ **57.519,05**	€ **101.870,14**	€ **80.417,23**	€ 21.392,73	-€ **77.353,20**	-€ **61.063,33**	€ 24.516,93	€ 19.353,89	
24	1,30	€ 99.170,77	€ 4.958,54	€ **19.125,79**	€ 347.097,71	€ 6.941,95	€ **56.527,34**	€ **101.870,14**	€ **78.074,98**	€ 21.392,73	-€ **75.653,13**	-€ **57.981,83**	€ 26.217,00	€ 20.093,15	
25	1,34	€ 85.003,52	€ 4.250,18	€ **18.417,43**	€ 297.512,32	€ 5.950,25	€ **55.535,63**	€ **101.870,14**	€ **75.800,95**	€ 21.392,73	-€ **73.953,06**	-€ **55.028,02**	€ 27.917,07	€ 20.772,92	
26	1,38	€ 70.836,27	€ 3.541,81	€ **17.709,07**	€ 247.926,93	€ 4.958,54	€ **54.543,93**	€ **101.870,14**	€ **73.593,15**	€ 21.392,73	-€ **72.252,99**	-€ **52.197,10**	€ 29.617,14	€ 21.396,05	
27	1,43	€ 56.669,01	€ 2.833,45	€ **17.000,70**	€ 198.341,55	€ 3.966,83	€ **53.552,22**	€ **101.870,14**	€ **71.449,66**	€ 21.392,73	-€ **70.552,92**	-€ **49.484,40**	€ 31.317,21	€ 21.965,26	
28	1,47	€ 42.501,76	€ 2.125,09	€ **16.292,34**	€ 148.756,16	€ 2.975,12	€ **52.560,51**	€ **101.870,14**	€ **69.368,61**	€ 21.392,73	-€ **68.852,85**	-€ **46.885,44**	€ 33.017,28	€ 22.483,16	
29	1,51	€ 28.334,51	€ 1.416,73	€ **15.583,98**	€ 99.170,77	€ 1.983,42	€ **51.568,80**	€ **101.870,14**	€ **67.348,16**	€ 21.392,73	-€ **67.152,78**	-€ **44.395,90**	€ 34.717,35	€ 22.952,26	
30	1,56	€ 14.167,25	€ 708,36	€ **14.875,62**	€ 49.585,39	€ 991,71	€ **50.577,09**	€ **101.870,14**	€ **65.386,56**	€ 21.392,73	-€ **65.452,71**	-€ **42.011,60**	€ 36.417,43	€ 23.374,96	
		€ 425.017,60	€ 329.388,64	€ 754.406,24	€ 1.487.561,60	€ 453.706,29	€ 1.941.267,89	€ 3.056.104,06	€ 2.432.238,13	€ 641.781,85	-€ 2.695.674,13	-€ 2.169.532,67	€ 360.429,93	€ 262.705,46	

Case Data	Project	Project capital cost	€ 2.125.088,00
	Lease	Equity Ratio	30,00%
		Equity	€ 637.526,40
		Cost of Equity Investor (Fixed IR)	5,00%
		Debt Ratio	70,00%
		Debt	€ 1.487.561,60
		CoD Debt (Fixed IR)	1,50%
		Residual Value	€ 212.508,80
		Residual Value (%)	10%
		Share Equity	1,00%
		Share Debt	1,05%
		WACC Lesor (IR)	2,05%
		WACC Lessee (IR)	2,60%

FIG. 3.11 30-year cash-flow analysis from the perspective of the Facades-as-a-Service provider. A Special Purpose Vehicle with combined equity and loan capitalisation has been used in this example.

The time-scales involved in the construction industry, easily reaching 30 to 50 years, make any projections related to these factors highly uncertain, and further research and time are needed to accurately address these issues. The project consortium is working with the Dutch metal facade industry branch organisation, VMRG, and other research institutes and projects, to advance our understanding of residual value and re-manufacturing techniques for façades and other building systems, hoping this information will soon contribute to the bankability of such products.

As seen on [Figure 3.9], the cash-flow analysis for the SPV over a 30-year contract period is promising, and results in positive gains a few years after completion of the project. This methodology must be further developed and tested on a number of different projects and scenarios, and with diverse stakeholder characteristics. The main financial challenge to implementation at the moment of writing is to identify the investor profile that could be better-suited to provide equity investment for such a model. The return on equity is lower than what is commonly offered by traditional real estate investments, while the cash-flow based form of financing makes full debt-based finance too risky a proposition. Under certain circumstances, and with certain types of projects and clients, the financial model is expected to eventually become safe enough for pension funds and other institutional investors to find it interesting.

Early adoption, however, will most likely be too risky for such parties, and a number of trials must be first successfully realised in order to build a positive track-record and support future investments.

3.3.3 TU Delft CiTG FaaS pilot project conclusions

After 2 years of work buy a broad range of experts in the different disciplines involved, the East façade of the CiTG building was replaced with a new FaaS-ready façade system in late 2019. The scientific outcome of this pilot project represents the main body of this thesis and is further described in Chapters 5 to 7. The key conclusions which could be taken from the pilot project are summarised below:

- FaaS contracting alternatives can be implemented within the current systemic built environment framework in terms of financing, building law, and managerial processes. This implementation, however, requires high customisation of processes, and therefore involves a more extensive time allocation, costs, and risk-bearing willingness from the involved parties.

- For PSS-based models, such as FaaS, to become applicable to a more mainstream portion of the built environment, this customisation must translate into standardised processes. This requires the active involvement of investors, banks, and real estate valuators (project finance perspective), regulatory, legislative, and fiscal policy bodies (building and tax law perspectives), and real estate developers, facility managers, architects, builders, and engineers (managerial perspective).

- A joint long-term collaboration between building owner, end-user, facility manager, and FaaS service provider can result in significant financial and technical incentives which can result in a better implementation and use of façade-integrated technologies. The currently ongoing asset management work, involving the servicing, cleaning, and maintenance of the façade, and the calibration of smart façade operating algorithms, continues to result in a more energy-efficient and comfortable indoor environment.

Chapter conclusions

This chapter has outlined the use of full-scale pilot projects as the main foundation for the research presented in this thesis. Only through full-scale prototyping, involving all the relevant stakeholders, experts, and decision-makers, can the question of Product-Service System and Circular Economy transition in the built environment shift from a theoretical proposition to a series of practical steps.

To place this into context, the findings of the EWI pilot project pointed to technological readiness of the different façade-integrated systems not being a crucial problem or a source of major uncertainty or risk. Willing façade assemblers exist, who recognise the value of collaborative work and product-service integration at a building envelope level. The logistics process and the contribution of system suppliers is quite streamlined in the industry, so that the technically innovative panels could be delivered, installed, and operated with only minor organisational challenges. Additional planning effort and willingness to cooperate were necessary than in a traditional building project, but such collaboration could be achieved and doesn't appear to be the reason behind integrated façades not being organically adopted as a more mainstream technical solution.

In order to both promote the implementation of integrated façades and do so through PSS and CE inspired performance contracts, the challenge moves beyond the technological, and instead requires the involvement of financiers, demand-side procurement and project management experts, building law professionals, and other stakeholders.

The disciplines represented by these stakeholders have been shaped by centuries of linear thinking, and therefore carry significant inertia and an unlikelihood to change organically. The following chapters will break down the different challenges, barriers, opportunities, and solutions which could lead to the implementation of FaaS and other PSS alternatives in the built environment.

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4 Drivers and barriers to the delivery of integrated Facades-as-a-Service

The chapter has been published in the professional, peer-reviewed Dutch publication "Real Estate Research Quarterly" - in a special issue dedicated to ongoing PhD research in the field of property development, management, and procurement – as "Azcárate-Aguerre, J. F., T. Klein, A. C. Den Heijer, R. Vrijhoef, H. D. Ploeger and M. D. I. Prins (2018). "Façade Leasing: Drivers and barriers to the delivery of integrated Facades-as-a-Service." *Real Estate Research Quarterly* 17(3)."

ABSTRACT

The construction and renovation of the building envelope represents a significant fraction of a project's life-cycle costs. It also has a determinant effect on the potential reduction in energy use, as well as on the improvement of the building's indoor comfort. Nevertheless, the challenge of a low rate and depth in building energy renovations cannot be solved through technological innovation alone. Instead, the Façade Leasing research project proposes a systemic shift in economic and business incentives, towards the creation of a performance-based contracting model for integrated Façades.

Façade Leasing explores an integral, cross-disciplinary model promoting accelerated strategic investment in energy-efficient building envelopes. A focus on performance delivery, rather than product sales, would in turn impulse ongoing innovation in products and management processes. It would also provide the foundations for Circular Economy (CE) strategies for the reuse and re-manufacturing of building components, leading to a potential reduction in primary raw material consumption across the façade industry.

This study starts by describing the “EWI Façade Leasing pilot project” developed and built at the TU Delft campus by a consortium of academic and industry partners. It then outlines the main drivers and barriers to the commercial application of the Façade-as-a-Service concept in the Dutch public, non-residential real estate sector, from the perspective of four key stakeholder groups: Demand drive, or the decision-making process of real estate developers, owners, and managers; Supplier readiness, or the necessary reorganisation of products and processes along the supply-chain; Finance, or the distribution of financial resources bridging the gap between initial investment cost and long-term service fees; and Governance, or the necessary regulatory innovation required to separate ownership of building and façade.
The research shows that, while further research and validation work is needed to test these principles in a controlled, case-study setting, the potential for façade-as-a-service delivery is within reach under the current legal and economic environment.

Chapter summary

This chapter analyses the Façades-as-a-Service concept from the perspective of four main stakeholder groups identified in the previous chapters: Demand drive (real estate management), Supplier readiness (Technology), Finance, and Building Law. It then establishes a breakdown of drivers and barriers to current implementation of PSS models in building envelope procurement. Lastly, it elaborates an economic flow-chart displaying key interactions and value propositions exchanged between stakeholders in the proposed Façades-as-a-Service model.

As has been previously described, barriers to the implementation of more efficient façade systems lie not in the technological readiness of adequate building systems. It results, instead, from managerial and commercial processes and knowledge transfer mechanisms leading to suboptimal technical decisions during a project’s planning and operational phases.

Decisions regarding the building stock, both existing and new, rest mainly in the hands of investors, developers, and facility managers. In the case of the Netherlands, the construction industry is largely dominated by the general contractor figure. Knowledge transfer between supply and demand is thus filtered through the often-conservative perspective of this central stakeholder. The market reception of innovative technologies is prevented by knowledge transfer barriers, project development sequences, and by the higher risk perception frequently attached to new systems by clients and general contractors (Cleton, 2015; Klein, 2013).

The demand side of the sector, meanwhile, is far from homogeneous. Private, corporate, and public organisations are characterised by widely diverse internal processes, economic incentives, and strategic goals. This organisational diversity often has a more determinant effect on the decision-making priorities of the organisation than the use, typology, or technical characteristics of their building portfolio.

Existing financial and legal systems are not immediately ready to adjust to the fundamental changes required by a CE transition enabled by PSS business models. Changes in the nature of economic transactions and ongoing financial and legal relations between clients, suppliers, and investors demand a reconceptualisation of many aspects of our legal and financial systems.

While the characteristics of the Dutch construction and real estate sectors are specific to the region, the outcome of a shareholder analysis identifies client profiles and strategic priorities which can be found in developed economies throughout Western Europe and even globally. International up-scaling potential is discussed in Chapter 8. Conclusions and discussion on the Façade-as-a-Service model’s applicability and up-scalability potential.

4.1 Introduction

The share of global environmental impact for which the construction sector is directly or indirectly responsible has been well documented and is regularly quoted (Eurostat, 2017; Smith, 2003). Diverse impact mitigation goals have been established by regulatory bodies around the world to incentivise improvements both in terms of construction process and in the quality and efficiency of the new and renovated building stock. Until recent years, this debate largely focused on the energy consumption of buildings during their operational phase, and the gradual improvement that could be achieved through the application of innovative – and often active – building technologies (Allouhi et al., 2015; Konstantinou & Prieto Hoces, 2018).

This incremental process, with a focus on energy optimisation, has led to a significant increase in the complexity of construction techniques. Research and development in building envelopes has seen particular progress, as such systems have a distinctly determinant role in the overall energy and indoor-climate performance of the building. Multi-layered systems for both opaque and transparent building envelopes have become the norm, and a growing number of façade-integrated building services are constantly expanding the functionality and relevance of the building envelope (Athienitis, Bambara, O'Neill, & Faille, 2011).

This combination of envelope and service functions can result in the building envelope accounting for as much as 40% of a new building's construction costs (Parker & Wood, 2013). In the case of deep building retrofitting projects, in which site, structure, and other building systems are reused, a façade with integrated building services can make up over 90% of a project's initial investment (Dall'O et al., 2013). This rise in complexity and cost, however, has not always been followed by a thorough understanding of the effect such systems have on the Total Cost of Ownership (TCO) – both financial and environmental – of the building throughout its service life. This knowledge gap often results in suboptimal decisions being taken during a project's planning phase, where a focus on initial investment costs frequently prevents the adoption of more robust or energetically efficient systems. While technology advances to enable the construction of energy-neutral and even energy-positive buildings, the market-integration rate of such technologies tends to be slow, and often limited to a small group of elite projects (Mlecnik, Visscher, & Van Hal, 2010). The cause for this, this paper argues, lies in the economic and organisational processes underlying the system, rather than the availability or reliability of new, high-performance technologies.

A second challenge presented by a focus on energy performance is the effect this rising complexity has on the use and disposal of material resources. Emerging, low-carbon building technologies – from energy-generation and distribution systems to smart, user-responsive micro-grids – are quickly merging into what we would traditionally consider the Electrical and Electronic Equipment (EEE) sector. The demand on materials, in terms of both volume and diversity, is therefore growing exponentially (Vidal-Legaz et al., 2016): From the high-volume elements commonly used in construction, to the highly-specialised micro-volume elements needed to produce integrated circuits and other EEE components which are becoming increasingly embedded in our buildings (BIO Intelligence Service, 2013; Ecorys, 2014). While the construction industry has focused on an incremental improvement in terms of operational energy use, it has often overviewed the consequences of such decisions in terms of the embodied energy and CO_2 content of products and processes, the reliability of global supply-chains, or the eventual depletion of finite and highly valuable material resources.

The concept of a Circular Economy is a response to this material resource challenge, just as the energy efficiency movement has been a response to the environmental challenge presented by the use of mostly non-renewable energy generation sources. One of the key principles of the Circular Economy is to involve companies and other industrial organizations in the elaboration of new economic and business models for a more resilient use of resources. Energy-efficiency and other sustainable practices have often been seen as an additional short-term capital expense (i.e. a financial burden) for companies and their investors (Figge & Hahn, 2005). The Circular Economy concept, meanwhile, addresses this misperception by focusing on improving the overall strategic economic position of these companies, while safeguarding the long-term values of wider society (Webster et al., 2013). A circular use of components and materials should lower manufacturing costs while reducing vulnerability to international raw material markets; a focus on service delivery rather than product sales should stabilise cash-flows across the value chain, protecting stakeholders from the volatility of, for example, real estate supply and demand cycles (Alix & Vallespir, 2010, p. 659).

A number of authors have established a relation between the resource management theory behind the Circular Economy and the realignment of business incentives that can be achieved through the implementation of Product-Service Systems (PSS) (Mont, 2002; Walter R Stahel, 2016; Tukker, 2015). In line with other performance-based, pay-per-use models recently initiated in the construction sector, such as lighting and carpeting, the Façade Leasing project proposes the development of a PSS model for integrated building envelopes. The principle behind PSS models is to shift transaction value away from physical products, and instead assign this value to the performance results provided by these products to the target client and/or end-user (T. Baines & H. Lightfoot, 2013; Tukker, 2004). As a fixed and functionally critical system, however, the façade is subject to highly specific requirements – from the technical to the regulatory – which result in a new level of complexity in its transition towards performance-based contracting practices. The objective of this paper is hence to identify the knowledge gaps behind this complexity, the stakeholders these knowledge gaps are relevant for, and the incentives these actors might have to pursue a transition.

4.2 The EWI pilot project at TU Delft

FIG. 4.1 Photograph of the completed “Façade Leasing Pilot Project” at TU Delft’s EWI faculty building (Photo: Marcel Bilow, 2016)

In late 2016 construction was completed on the “EWI Façade Leasing pilot project” at the TU Delft campus in Delft, The Netherlands, see Figure 4.1. This mock-up façade renovation project consisted in the replacement of four unitary curtain wall panels at the building of the Electrical Engineering, Mathematics and Computer Sciences faculty (commonly known by its Dutch acronym, EWI). This iconic building, built during the 1960’s, has in recent years suffered a series of building service failures, and is increasingly criticised by users and operators for both its inflexible spatial layout as well as its inadequate indoor comfort. The building has been therefore deemed the ideal target for a façade renovation prototype, particularly one showcasing the potential benefits of decentralised, façade-integrated building services. Its curtain wall façade, technically innovative for its time, consists of a ventilated, double-skin system, with an exterior single-glazed, metal-framed layer and an interior wooden-framed layer. The building layout, a long central corridor with adjacent offices and meeting rooms on both sides, provides the room depth and façade-to-floor ratio necessary for decentralised building services to perform effectively.

The purpose of the pilot project was twofold: On the one hand, it was intended to act as a technical demonstrator of the technological range and readiness of new, decentralised, façade-integrated technologies. Such technologies, not all of which were physically installed in the prototype due to financial or time constraints, include systems such as BiPV energy generation and storage, diverse interior, in-glass, and exterior sun-shading systems, ventilation and air-handling devices, automated operable windows, LED media façade elements, and self-supporting green façade systems. The pilot project, therefore, intended to showcase the wide range of façade-integrated services currently available on the market, and their capacity to deliver most, if not all, of the indoor comfort regulation services necessary for certain building typologies.

On the other hand, the pilot project acted as a central case-study promoting further discussion within a wide-ranging consortium regarding the business and supply-chain modelling implications of a transition from façade product delivery to integral indoor comfort service provision. The consortium – made up of real estate investors and operators, façade fabricators, system suppliers, and industry branch organisations – as well as the design and engineering process followed to execute the project, have been described in the paper "A business-oriented roadmap towards the implementation of circular integrated Façades" (Azcárate-Aguerre, Klein, & den Heijer, 2016).

The planning, execution, and evaluation phases of the pilot project highlighted many of the systemic circumstances which currently lead to a slow energy renovation rate, and to suboptimal decision-making and missed opportunities in the technical depth of such renovations.

4.3 Methodology

While the EWI pilot project confirmed the commercial attractiveness of CE and PSS principles to a diversity of industry parties on both sides of the value chain, it opened new questions regarding the practical implementation of a performance-based business model for integrated Façades. Further research has therefore been oriented towards understanding the current procurement and knowledge-sharing mechanism dictating projects' planning and execution phases, as well as exploring the impact a service-based façade contracting method could have towards improving technical decisions in new buildings and building envelope retrofitting projects. The research has been based on a series of interviews, working sessions, and public presentations, in which the research team actively engaged experts across the most relevant stakeholder groups within the construction and real estate sectors in the Netherlands. The stakeholders have been asked to identify and elaborate on the main drivers and barriers they would expect in the implementation of a Façades-as-a-Service model.

Data gathered through this field exercise has then been compared and complimented with literature references and case-studies. These references have been largely collected from other economic sectors, such as the automotive and industrial design industries, with more experience in the application and financing of PSS business models.

Finally, a schematic business and value model has been created for the possible organisation of a façade-as-a-service contracting process. This model has then been evaluated by representatives of the different stakeholder groups, and a summary of cross-organisational drivers and barriers has been reached.

4.4 Stakeholder analysis

Following the methodology previously described, the objective of this analysis has been to map the current priorities and concerns of key players within the construction value chain. This map has then been used to develop a schematic plan to maximize potential collaboration between long-term client needs and key supplier and fabricator skills under a performance-based contract. While the "Façade Leasing Pilot Project" focused on the technological aspects of the Façades-as-a-Service concept, this stakeholder analysis led to specific suggestions –according to diverse fields of expertise –on its managerial aspects, and how this business model could be successfully implemented in a realistic setting.

4.4.1 Real estate owners and operators

The demand side of the built environment is represented by organisations that either own and/or use buildings (and land). When there is an intervention or transaction, they become clients that pay for products and/or services. As owners of buildings, clients will focus on residual value, life cycle costs, and return on investment.
As users of these buildings, clients will concentrate on how their organisational performance is affected by the building.

Exploring new business models to match innovative supplier solutions with changing client demands gets most interesting when the owner and user perspectives are combined in a single client. Only then the strategic, functional, financial, and physical values need to be considered by one stakeholder (den Heijer, 2011). For this reason the research team focused on a specific client profile: the owner-user (or owner-occupier) of buildings. Dutch universities are examples of organisations that combine ownership and use of their buildings. The uncertainty in demand and the required flexibility in the functionality of buildings also plead for more flexible façade solutions, of which Façades with integrated decentralised systems could be an example. TU Delft, as one of these organisations, served as a test case - and living lab - to identify "demand drive".

The most fundamental factor determining the success of a new business model is the client's willingness to invest in its added value proposition. In economics "willingness to pay" is connected to "value". Since value is hard to operationalise - if it combines strategic, financial, functional, and physical aspects - the extra payment is equally difficult to calculate. However, the incentives to invest in a product-service combination, rather than a product, can be made explicit.

As owners of buildings, clients are becoming increasingly socially responsible, environmentally conscious, and willing to invest in resource-efficient solutions that contribute to a more Circular Economy. Of course, financial incentives still play a role that is larger for commercial organisations and smaller for organisations that are funded with public money, like universities. Residual value, or the value of reused components and materials, and lower energy costs are demand drivers: they influence decision-making by owners of buildings.

As a user of buildings a client is increasingly aware of the shorter functional lifetime of building systems and the high costs of either new investments or decreasing productivity (den Heijer, Arkesteijn, de Jong, & de Bruyne, 2016). Anything that jeopardises the performance of the organisation could have considerably higher costs and risks than implementing more flexible solutions or more flexible processes to provide a service. Clients are therefore receptive towards the concept of paying for a performance and service while not having to put in the effort, and hire the staff necessary, to support it. They also acknowledge that this is simpler for well-defined performances, like “enough light for the activities in the room” than for “keeping us comfortably productive”. The more complex the primary processes, the more complex it is to establish performance indicators against which correct performance can be measured and hence productivity guaranteed.

The potential negative impact of a suboptimal decision, during the building envelope planning and construction phase, could be disproportionately high at a business operational level. While a building envelope with integrated services can, as mentioned, represent as much as 40% of a new building project’s initial cost, this total initial cost is deemed to represent only about 40% of an average project’s TCO (Ive, 2006). Furthermore, the building’s TCO generally represents only about 12% to 15% of a business’ operational expenses over the project’s service-life (e.g. 30 years), while the other 85% to 88% consists of non-building-related human and material resources needed to run the business (Hughes, Ancell, Gruneberg, & Hirst, 2004). Savings in initial investment, for example by procuring a lower-performance façade, can therefore have exponential negative consequences for the business’ bottom-line. These consequences would be the result of higher operational costs – for example due to a higher building energy consumption – and to a potentially even larger extent due to a drop in staff productivity as a consequence of poor indoor comfort (Loftness, Hartkopf, & Gurtekin, 2003; Terrapin Bright Green, 2012).

From both the owner and user perspective the long-term relationship with suppliers is important for safeguarding shared responsibility for sustainability goals, by being able to adapt to new standards, change components, or upgrade existing systems to innovative solutions during the functional lifetime of the building. Trading uncertainty for certainty, even at the cost of a higher financial fee, can be preferable.

4.4.2 Façade fabricators and system suppliers

Traditionally in the façade supply chain the contractor is the integrator. Suppliers as well as designers play a minor role, particularly in the Netherlands. Besides, the role of the client and demand specifications are dominant, with over-specified tenders focused on technical solutions rather than outcome (Uyarra, Edler, Garcia-Estevez, Georghiou, & Yeow, 2014). Contractors and thus suppliers tend to follow demand rather than developing and supplying integrated products.

In the near future the role of contractors is expected to decrease. This offers the opportunity for groups of suppliers to potentially take over the role of system integrators of sub-assemblies including the façade. In such a scenario the business model for coalitions of suppliers would be to develop circular products and develop leasing, upgrading, or take-back services for those products. This is dependent on financial and legal implications for coalitions of suppliers and whether they will be able to cope with and co-organize those responsibilities within the group of firms. In fact the supply chain of suppliers would then act as a single ‘quasi-firm’ (Eccles, 1981) or ‘extended enterprise’ (Boardman & Clegg, 2001). The quasi-firm points towards the notion of coalitions of firms behaving as one firm. This raises the issue of core competencies of firms together making up an ‘extended enterprise’ in a resource-based view (Prahalad & Hamel, 2000).

The extended enterprise implies a higher level of integration between firms. In order to achieve higher levels of supply chain integration, there is a need to strengthen inter-firm relationships, achieve mutual benefits and build trust (Dainty, Millett, & Briscoe, 2001). Then the extended enterprise will be able to be the single point of contact with the client, façade manufacturer, and service provider. In most supply chains one of the firms would be the ‘system integrator’ who will lead and integrate the whole supply system. Generally, this is the largest firm in the supply chain, taking most of the financial risk. The integration of the supply system is not only driven by economic arguments but also includes organisational and social aspects between firms and teams of people involved (Bridge, 2005).

4.4.3 Financial organisations

Regardless of scale, project financing in the real estate sector has traditionally been secured by the market value of the real estate property which is being financed. This value, while sensitive to volatile trends such as the behaviour of the real estate market, can in most cases be effectively calculated based on a long industry track-record taking into account factors such as location, quality, function, year of construction, operational risks, among many others (Pagourtzi, Assimakopoulos, Hatzichristos, & French, 2003).

The loss of basic functionality, for example if the building envelope is missing or inoperative, can have dramatic consequences on the project's financing model, as a building without an operative Façade is not occupiable. It therefore loses its quality as a complete asset which can be directly sold on the market. This loss of value due to functional incompleteness is the main concern behind property law (as will be discussed in the following section).

A fully CE construction supply chain is likely to result in a building which is no longer a single integration of components and materials which fulfil a rentable function, but instead would become a collection of ongoing service-contracts connecting a large number of suppliers and service providers. Ownership of diverse building systems would be held by a number of parties, meaning no functionally solid and fully transferable real estate property could be defined.

Looking at the specific case of the building's Façade being used as an asset to secure a loan by the Façade manufacturer, it is deemed to be an unlikely proposition. The Façade, if removed from the building, has minimal intrinsic value. Reselling the Façade elements in the market would most likely result in high disassembly, transportation, storage, and re-manufacturing costs, which would render the whole exercise economically unfeasible. The value of raw materials, even under the most optimistic forecasts, is not likely to become high enough to justify the process by simply reusing these materials as raw industrial input. Since the physical asset (the Façade) holds no significant residual value, an asset-based loan is not an option.

Innovative cash-flow-based project financing mechanisms, such as those being used in the wind energy sector, could provide a solution to this financing barrier. If energy improvement performance can be reliably backed by a documented body of energy-renovation projects, the income and productivity resulting from the renovation could act as guarantee, securing the necessary cash-flow to cover the loan repayment. Such is the mechanism behind the growing Energy Service Performance Contracting (ESPC) model (Sorrell, 2007). Since track-record history and risk assessment methods are yet to be developed for the financing of façade renovation project, large and financially solid client organisations - such as publicly-supported universities - could provide the ideal circumstances for a commercial pilot project. Their operational stability and above-average credit rating would act as further guarantee of service fee payment.

4.4.4 Governance

Circular Economic practices based on the delivery of performance services depart radically from the traditional ownership model on which property law has been based since Roman times. Construction projects have been traditionally considered as functionally complete entities. A developer will procure a plot of land, and the human and material resources necessary to erect a building. The building will then be sold either as a whole or subdivided into functional units such as apartments or offices.

Even if a diversity of transaction models exists, full ownership of a complete, functional space unit measured in terms of square metres between structural walls, has been the legal construct by which real estate value is calculated. Financial and Legal aspects of a Circular Economy model for construction are therefore closely tied.

To move the Façade-as-a-Service concept forward, perhaps the most important distinction to start with is that between legal ownership and economic property. While the latter is not a notion in the Civil Code, it is particularly relevant in fiscal law.

Legal ownership is a generally understood concept, it represents "an enforceable claim or title to an asset or property, and is recognized as such by law" (BusinessDictionary.com, 2018). The owner of the land will normally be also owner of the buildings constructed on it (the buildings being fixtures) as well as of the building's constituent parts such as slabs, walls, roof, doors, and windows. Economic ownership allows a user to obtain full enjoyment of the object, including bearing financial risk for it, while not being its legal owner. Long-term leasing of real estate property such as land or built objects is another example of such a structure (Ploeger, Prins, Straub, & van den Brink, 2017).

In principle, immovable property is not an absolute right, but may be determined through the establishment of building lease contracts, keeping ownership on the side of the manufacturer or a third party such as a lessor. Lack of precedence doing this specifically for Façades means that no guarantee of its success can be given without a pilot case in which the appropriate contracts can be structured and tested against property and fiscal law. Previous contracts elaborated for elevators and solar panels owned by third parties show that it can be done in theory, but it depends on how much the Façade, or some of its components, can be argued to be independent of the building's core functions.

4.5 The Façade-as-a-Service model

The stakeholder analysis presented above has resulted in the elaboration of a schematic model (see Figure 4.2) for the contracting of performance-based façades-as-a-service. This model considers the core competences of the diverse stakeholders, the ongoing relations between partners, as well as sources of long-term social and corporate value beyond the directly financial. The model makes a distinction between tangible products and the intangible services delivered by such products. It also proposes a stepped transition in which, at first, only the service provider needs to engage in PSS activities, while second-tier suppliers and sub-suppliers continue to provide product-based offerings. Such a gradual supply-chain reorganisation process is deemed to be a more likely proposition than a radical, cross-industry shift.

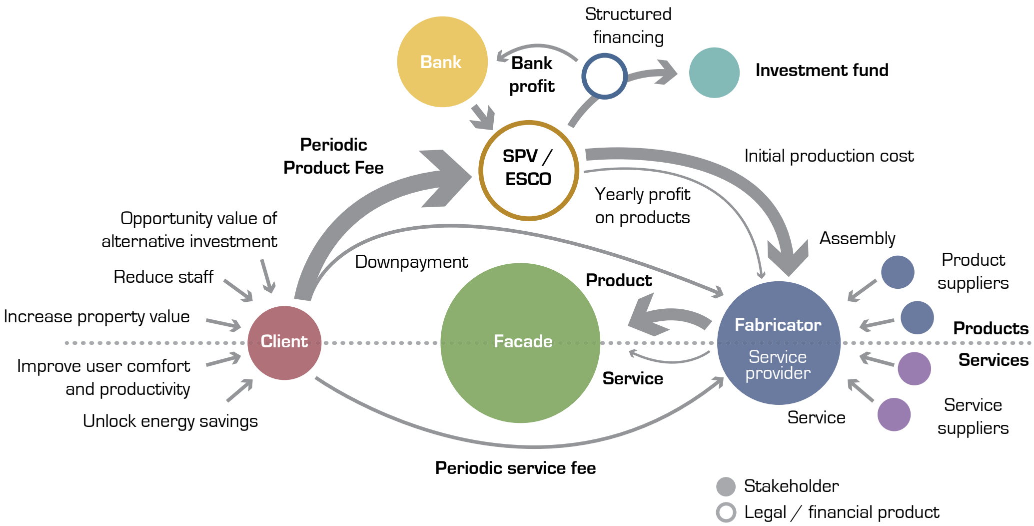

FIG. 4.2 Schematic Façade-as-a- Service model of stakeholder relations, activities, and forms of value creation in a service-based façade contracting model.

TOC

The Façade-as-a-Service model has been evaluated by representatives from the diverse stakeholder groups. A summary of the main drivers and barriers identified by these actors has been elaborated and is presented in Table 4.1.

TABLE 4.1 Selected drivers and barriers to the implementation of façade-as-a-service contracting model, according to main stakeholder groups.

	Drivers	Barriers
Client	Outsource non-core processes.	Partial third-party ownership of organisation's real estate.
	Accelerate rate and depth of portfolio retrofitting.	Cash-flow based financing limited for smaller clients.
	Stabilise cash-flow, lower upfront capital requirements.	Possibly high risk-premium while track-record is created.
	Improve functional flexibility of portfolio.	Contract setup and management costs.
Service provider	Access to new service-based markets.	Lower upfront profit.
	Stabilise cash-flow, reduce impact of real estate cycles.	Development of new processes required (staff and training).
	Higher profit margin for services. Incentivise innovation and quality.	R&D investment on system and service integration.
	Raw material security.	
Financier	Open market for new financial products.	Lack of track-record.
	Conform to green / ethical banking practices.	Higher perceived risk due to lack of physical collateral.
	Value creation for large and financially solid clients.	Complexity of split ownership and divided responsibilities.

4.6 Conclusions

The state-of-the-art in façade-integrated technologies is often overlooked due to the knowledge-transfer process between the technical experts responsible for the project development and construction, and the managerial experts responsible for the investment in, and operation of, the building (Klein, 2013). A focus on lower initial investment cost still widely dominates the sector, and defines most procurement processes. Such focus favours products and systems which are often simpler, lower-performing, or subject to require a higher maintenance effort. Such decisions could result in a higher TCO – in terms of both financial and environmental impact – than the use of more robust, higher-performance alternatives which also entail a higher initial investment.

The assumption of this project, and indeed of PSS theory in general, is that the alignment of long-term interests between suppliers of products and consumers or users of such products could lead to a more efficient management of global resources. Both ends of the construction value chain could co-create a new value segment by sharing the burden of managing a building's life-cycle according to their core skills and competences. Ownership of materials and responsibility for the effective and updated function of components would be retained by parties with experience in the manufacturing and development of technology, reducing the need for duplicated knowledge. This could meanwhile expand the economy of scale potential of suppliers beyond the production phase and into the ongoing operational, service-delivery phase.

A comprehensive methodology to compare linear and circular contracting processes in terms of their Total Cost of Ownership is still necessary. The TCO needs to be balanced against the Total Value of Ownership (TVO) when managing a building portfolio. This long-term value balance is not easy to assess, especially for non-profit organisations. But even the TCO is not easy to measure: allocation of capital costs, maintenance costs, and energy costs to specific spaces and users is quite difficult within large organisations or for large buildings. The owner and user of buildings can find incentives to implement a new business model in: safeguarding user productivity during the lifetime of the building, reducing internal management staff, saving energy expenses, having liquidity for (or higher yields from) alternative investments, and increasing the residual value of their property as it reaches its end-of-service.

Large amounts of data from diverse stakeholders must be analysed and organised to create a map of direct and indirect costs and savings resulting from the reorganisation of the supply-chain. In the past fifteen years universities have worked hard to improve databases, compare ratios, and generate management information to support campus decisions (den Heijer et al., 2016). Determining value and costs has become easier, but still requires thorough scenario and risk analysis for new business models. As has been proposed by other authors, public procurement offers a low-risk, long-term environment which can catalyse early adoption of innovation in technologies and processes (Edler & Yeow, 2016). To support this, practice-oriented research such as the one hereby presented provides intermediation between stakeholders with diverse, and often conflicting, commercial interests.

More effective decision-making tools could support long-term, multi-stakeholder planning, and unlock more sustainable contracting models for the construction industry, resulting in a lower consumption of energy and material resources. The business model and stakeholder analysis described in this chapter show that, in principle, all stakeholder groups identify potential value creation in the pursuit of this Circular Economy-inspired model. It also shows that the key assumptions behind more sustainable industry practices within a CE and PSS frameworks can be achieved in such a specific and practical example as that of Façades-as-a-Service.

Significant shifts have to be done in certain areas: for example, the transition from asset-based to cash-flow based financing of real estate described in the Financial section 4.4.3; as well as distributed ownership models based on fiscal economic ownership practices and creative application of apartment law, as described in the Governance section 4.4.4. However, such shifts are not, in principle, radically innovative, and can build upon contracting and procurement models for which similar precedents exist.

Chapter Conclusions

This chapter has broken down the practical implementation of a FaaS model into four broad key stakeholder groups in the Dutch construction and real estate sectors: Management, Technology, Financing, and Building Law. A number of drivers and barriers have been identified for each group, and a long-term value map of expected stakeholder transactions has been elaborated.

The following four chapters will look in more depth at each of the four stakeholder segments identified, with the goal of better understanding these drivers and barriers and provide possible solutions or new evaluation mechanisms supporting the model's implementation.

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5 The technological dimension

Façades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope

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ABSTRACT The servitisation of the built environment, through the implementation of product–service systems, is considered a promising business strategy to achieve a circular economy transition. This servitisation faces a number of practical challenges, among them the technological readiness and effective integration and application of existing and emerging products, manufacturing processes, and digital monitoring and management tools. The research builds on targeted literature review, and on a research-through-design approach based on full-scale pilot projects developed in an ongoing feedback loop between researchers, planners, and industry partners representing both the demand and supply sides of the façade industry in the Netherlands. The paper analyses the technical implementation challenges currently preventing the façade industry from adopting performance-based contracts. It then proposes the roles that existing and emerging digital design and engineering technologies, manufacturing processes, and asset management systems can play in the development, implementation, and fulfilment of such contracts. The paper proposes a multi-stakeholder, systemic model for the development and application of façade technologies capable of overcoming many of the technical implementation barriers to the delivery of performance-based contracts for integrated façades. From this it concludes that an effective development of building technologies should strategically align with the solving of economic and contractual challenges such as circularity-readiness, profitability, risk distribution, legal demarcation, performance monitoring, and residual value stewardship. The resulting framework provides a strategic and conceptual basis for the development of circularity-enabling façade technologies, accounting for the diverse and sometimes conflicting interests of the multitude of stakeholders involved throughout a project's life-cycle. The framework aims to support planners, manufacturers, and builders to accelerate the circular deep energy renovation of the built environment while also exploring new business opportunities.

KEYWORDS façade engineering; circular economy; product–service systems; energy renovation; built environment; performance contracts; facades-as-a-service; service integration

FEATURED APPLICATION The research proposes a strategic path to align future development in façade and façade-integrated technologies with the new economic, legal, and organisational requirements of a more sustainable, circular, and performance-based façade industry.

Chapter summary

It has been stated before in this thesis that technological development alone (i.e. supply push) is not proving a strong-enough driving force for the clean energy and Circular Economy transitions in the built environment. Current and emerging building technologies, however, will have a strong influence on the implementation of Product-Service Systems. As Facades-as-a-Service providers move their commercial operations as close as possible to the core needs of their clients (T. Baines & H. Lightfoot, 2013), new hardware and software solutions must be applied to the control and monitoring of delivered performance. New engineering solutions and industrial processes must also be developed to safe-guard extended product guarantees and increase the residual value of equipment, thus enhancing the economic feasibility of its life-extension alternatives.

This chapter presents and discusses the value- and life-cycle-engineering possibilities unlocked in the planning, construction, and operation of the building envelope by the implementation of performance-based contracts. The study starts by laying out conflicts and inefficiencies in the traditional façade procurement and engineering process, including stakeholder involvement during different planning phases, split incentives, supply-chain barriers, short-termism, user interface, and a focus on minimising initial investment costs. It then lays out the impact of Façades-as-a-Service procurement model on the design, engineering, planning, construction, management, and end-of-service reprocessing of façades and façade-integrated systems.

The paper describes the possible role of emerging technologies in the development and implementation of a FaaS model. New business roles can be created and a faster technological update can be enabled, while improving the financial stability of stakeholders on the supply side of the façade value-chain in the face of volatile real estate markets.

5.1 Introduction

The contribution of the built environment and the architecture, engineering and construction (AEC) sector to global environmental impact indicators is profound and well-documented (Becqué et al., 2016; Gallego-Schmid, Chen, Sharmina, & Mendoza, 2020; Ness & Xing, 2017). In this context, the systemic transition theories of circular economy (CE) and product–service systems (PSS) have emerged as promising and potentially synergistic strategies to limit or reverse this environmental, economic, and societal impact (Ellen MacArthur Foundation, 2013; Material Economics, 2018; Michelini, Moraes, Cunha, Costa, & Ometto, 2017). Two fundamental aspects of CE theory—the de-materialisation of economic activities and the conservation of material resources within closed industrial loops—could have a considerable positive impact on the reduction of environmental degradation caused by activities related to the construction sector and the built environment.

Product–service systems (PSS) are a set of business and industrial strategies that propose to shift the key value in economic transactions away from the sale and transfer of material products and instead focus it on the effective and ongoing provision of performance services. Such strategies are often linked to the CE discussion due to the natural alignment of their incentive structures, value (co-)creation objectives, and potential de-materialisation effects (Allais & Gobert, 2016; Bressanelli, Adrodegari, Perona, & Saccani, 2018; Walter R Stahel, 2016; Tukker, 2015).

The implementation of CE and PSS principles requires, in practice, a broad restructuring of the economic, legal, financial, and technological foundations on which our current economic and industrial systems are based (Azcárate-Aguerre et al., 2018; Di Francisco Kurak, Barquet, & Rozenfeld, 2013; Hänsch Beuren, Gitirana Gomes Ferreira, & Cauchick Miguel, 2013). These challenges are particularly complex in the case of the construction sector, which is defined by large volumes of material use, long project timeframes spanning decades or even centuries, and specific legal and financial characteristics which are deeply embedded in our socio-cultural and economic environment, and which form one of the pillars of the global economy (Baum, 2009; Schwartz, 2009; van Loon & Aalbers, 2017). Along the transition towards a circular façade economy, the role of technical innovation is essential and diverse. Aspects such as the design and engineering of circular products and manufacturing processes, the monitoring of ongoing performance indicators, and the long-term tracking of embodied materials and maintenance schedules have a determinant effect on the technical feasibility, legal and managerial viability, and financial bankability of PSS offerings (Huizing, Schraven, Kooijman, & Mol, 2019; Stigter, Prins, & Straub, 2016; Joris Van Ostaeyen, 2014). In order to pursue PSS ambitions, manufacturing companies must build significant capacity and take on extended value chain activities beyond their traditional front-office sales (T. Baines & H. Lightfoot, 2013). Furthermore, even if a PSS-based value chain is achieved, critical and continuous review of product manufacturing, service delivery, and reverse logistics processes is required in order to translate circular intent into actual resource circularity (Kühl, Tjahjono, Bourlakis, & Aktas, 2018). All these circularity-enabling products and processes can be translated into a new set of functional requirements for façades and other building products. Such functional requirements can conceptually determine the contribution of specific components and practices to achieving specific circularity and/or servitisation objectives. They can also be used as the primary procurement input on which designers, engineers, planners, manufacturers, and builders can develop specific and strategically aligned technical solutions.

This study is one of the outcomes of the five-year façade leasing project, in which various consortia of academic and industry partners worked on the development and execution of two full-scale façade servitisation pilot case-studies. During the process the research team explored the different dimensions of the implementation challenge, from the technical to the organisational, financial, and legal. The innovative contribution of this work is the integration between technical façade functionalities and applications (Klein, 2013; Van Nederveen & Gielingh, 2009), economic and organisational challenges of PSS (T. Baines & H. Lightfoot, 2013; Joris Van Ostaeyen, 2014), and strategic circular economy objectives (Potting, Hekkert, Worrell, & Hanemaaijer, 2017; RLI, 2015). By collecting these theoretical priorities into a single conceptualisation framework—supported by current façade industry examples—the full picture of a PSS-based CE transition can be more easily understood, mapped, and co-developed by both academia and industry. In the increasingly mainstream discussion on PSS and CE, a growing number of manufacturers are marketing solutions claiming to achieve material circularity. In the absence of final consensus on how to measure and monitor effective material circularity, a framework is needed to relate services, functionalities, and technologies on the path toward delivering circular facade services. This framework can be used by both technology suppliers and project commissioners to define the changing role of technology in the delivery of circular building envelope solutions.

5.2 Hypothesis

The hypothesis underlying this study is that—in the transition towards a circular and performance-based façade economy—a new set of functional façade requirements is needed. This hypothesis follows from transitional PSS pathways reported by other manufacturing sectors with more extensive experience along the servitisation path (Fargnoli, Haber, & Sakao, 2019; Lerch & Gotsch, 2015; Pieroni et al., 2016; Romero & Rossi, 2017). The traditional, product-based technical solutions of a linear façade economy are commissioned and paid for by the building investor/owner and in the final interest of the building user or the facility manager. These façade functions focus on facilitating a safe, comfortable, aesthetically pleasing, and in some cases environmentally efficient indoor space for the building users, by deploying a range of physical and digital technical solutions (Akbari, Yazdanfar, Hosseini, & Norouzian-Maleki, 2020; Boeke, Knaack, & Hemmerling, 2019; Herzog, Krippner, & Lang, 2012; Klein, 2013; Martinez, Patterson, Carlson, & Noble, 2015). Once the construction phase is finalised these technical components must be maintained by a facility management team, frequently with limited or no further involvement from the original component manufacturers or from other technical experts involved in the planning and construction phases (Berg et al., 2012; Gholami & Lindegård, 2018; Jensen, 2009).

A new set of circularity-enabling façade functions must, in contrast, reflect and enable the long-term interests of a multitude of stakeholders, beyond the strictly necessary user-focused façade functions of the linear economy. These functions must also focus on the long-term preservation of the value embodied by the building through technical updating and upgrading to meet ever-changing internal and external demands (Wim Gielingh & van Nederveen, 2010). Examples of such extended functions include digital building information modelling (BIM) twins to allow live tracking of components and materials; tagging technologies to facilitate asset management by financiers and facility managers; remote monitoring technologies to enable proactive maintenance schedules, among many others (Pieroni et al., 2016; Sun, Chai, Pi, Zhang, & Fan, 2017). These extended circular functions are no longer strictly in the sole interest of the building owner or building user. They must therefore be commissioned and financed in a collaborative model that guarantees long-term value co-creation and sharing of technical responsibilities and economic incentives, while safeguarding the material stewardship and carbon efficiency interests of society as a whole. In this path, the study proposes to modify and expand upon the existing framework of technical functional requirements in order to unlock and enhance material circularity potential through extended stakeholder incentives and liabilities.

5.3 Materials and Methods

The study is based on three levels of research, bridging the gap between theory and practice. Due to the explorative nature of this research and the lack of directly comparable sources and references, the study instead draws inspiration from research in other manufacturing fields and tests the circular premises of this research against practical façade pilot projects developed in collaboration with large consortia involving dozens of industry partners and professional experts. The first step is a (non-exhaustive) literature study and desk research, the second and third steps follow a research-through-design approach in which specific technical challenges to PSS and CE implementation are balanced against existing functional requirements and technical solutions in an iterative process involving both supply and demand stakeholders (Ioannou, Klein, Konstantinou, Bilow, & Azcárate-Aguerre, 2022; Ruvald, Bertoni, & Askling Johansson, 2019; Stappers & Giaccardi, 2017; Zimmerman & Forlizzi, 2014).

5.3.1 Literature Study

The study builds on existing CE and PSS literature to identify the servitisation process followed by manufacturing companies—in some cases within but mostly outside of the construction sector-on their path towards incremental servitisation. A significant body of knowledge has been gathered in the last couple of decades which identifies the key strategic choices, technological innovations, and organisational drivers and barriers, which have enabled companies to effectively adopt transitional or full PSS operational models (Aurich, Fuchs, & Wagenknecht, 2006; Parida, Sjödin, Wincent, & Kohtamäki, 2014; Vezzoli, Kohtala, & Srinivasan, 2013). The literature research focused on scientific articles and reports related to previous experience with circular economy, product–service systems (and servitisation), and stakeholders' dialogue in manufacturing industries, which were also the main keywords in the search concepts. Scientific databases, such as Scopus were used, as well as experience of national and international projects found in the respective databases, such as Cordis (European Commission, 2021) and the EIT projects and publications library (European Institute of Innovation & Technology (EIT), 2021).

5.3.2 Stakeholder Mapping and Consultation

In order to identify the key aspects and requirements for the implementation of PSS models in the façade industry it is essential to collect the views and strategic priorities of the stakeholders' constellation. To this end, the study aimed, on the one hand, at mapping those stakeholders that are the potential adopters of a PSS—from both a supply and demand perspective. On the other hand, it aimed at consulting with them, in order to identify opportunities and bottlenecks in the process. Stakeholder mapping and consultation sessions were organised over a period of five years (between 2015 and 2020) through dozens of meetings with decision-makers, facility managers, end-users, designers and engineers, legal and financial advisors, manufacturers, builders, and system suppliers. General meetings were organised on a bi-monthly basis, with the participation of both demand and supply parties and addressing technical solutions to PSS implementation concerns identified during the planning phases of the pilot projects. Specific meetings with individual stakeholders-facility management, faculty end-users, central finance and legal departments, among others—were scheduled as required when facing discipline-specific challenges. These stakeholders were grouped into a sequence of consortia of academic and industry partners which participated in the development of the three stages of the "façade leasing" research project.

Drivers identified during this process include customer acquisition and retention through product decommoditisation, new revenue streams and financial stability, outsourcing of initial capital requirements and technical responsibility. Barriers to be overcome include the creation of legal contracts, financing and corporate structures, management practices, technological integration, and reverse logistics models for the recovery of materials and components. These organisational drivers and barriers have been described by Azcárate-Aguerre, et al. (Azcárate-Aguerre et al., 2018).

5.3.3 Case-Study Implementation through Full-Scale Field Prototypes

The case-study phase consisted of two field pilot prototypes (Koskinen, Zimmerman, Binder, Redstrom, & Wensveen, 2011) using fully operational TU Delft buildings as case studies during the façade leasing research project (2015–2020).

The project focused on (1) developing working, full-scale façade-as-a-service (FaaS) built prototypes, through which to identify technical drivers and barriers to implementation, and (2) finding organisational, managerial, and regulatory solutions to address these drivers and barriers, by exploring the legal, financial, and corporate implications of a PSS model for the contracting of facades-as-a-service (FaaS).

The two full-scale pilot prototypes built were:

- *The EWI faculty building Façade Leasing technical mock-up (2017),* in which was explored the technological readiness of modular façade-integrated technologies to deliver energy savings and indoor-comfort improvements in a generic meeting and lecture room at the target building (J. F. Azcárate Aguerre et al., 2016).

- *The CiTG faculty building large-scale demonstrator prototype (2019),* in which were explored the broader systemic drivers and barriers to the implementation of façade-integrated technologies through a PSS contract, beyond the purely technical. The project resulted in the deep energy retrofit of over 2.600 m^2 of the target building's façade (J. Azcárate Aguerre, Klein, & den Heijer, 2019; Azcárate-Aguerre, Klein, & Den Heijer, 2019). Figure 5.1 shows the new CiTG façade system, which includes centrally monitored and controlled operable windows, an upper ventilation window to enable night-cooling during warm summer nights, and vastly improved thermal performance of both framing and panelling.

In the process of engineering and developing the FaaS pilot projects we listened to the requests of diverse stakeholders for new and existing functional requirements which need to be physically or digitally in place in order to enable the construction, financing, operation, management and/or monitoring of a FaaS contract, as well as the high-value maintenance and recovery of components and materials. This research-through-design approach was based on an ongoing feedback loop between researchers and stakeholders during a design, engineering, and planning phase spanning almost a year—in the case of the small-scale EWI pilot project—and nearly two years in the case of the CiTG large-scale pilot project. The research-through-design feedback loop is illustrated in Figure 5.2.

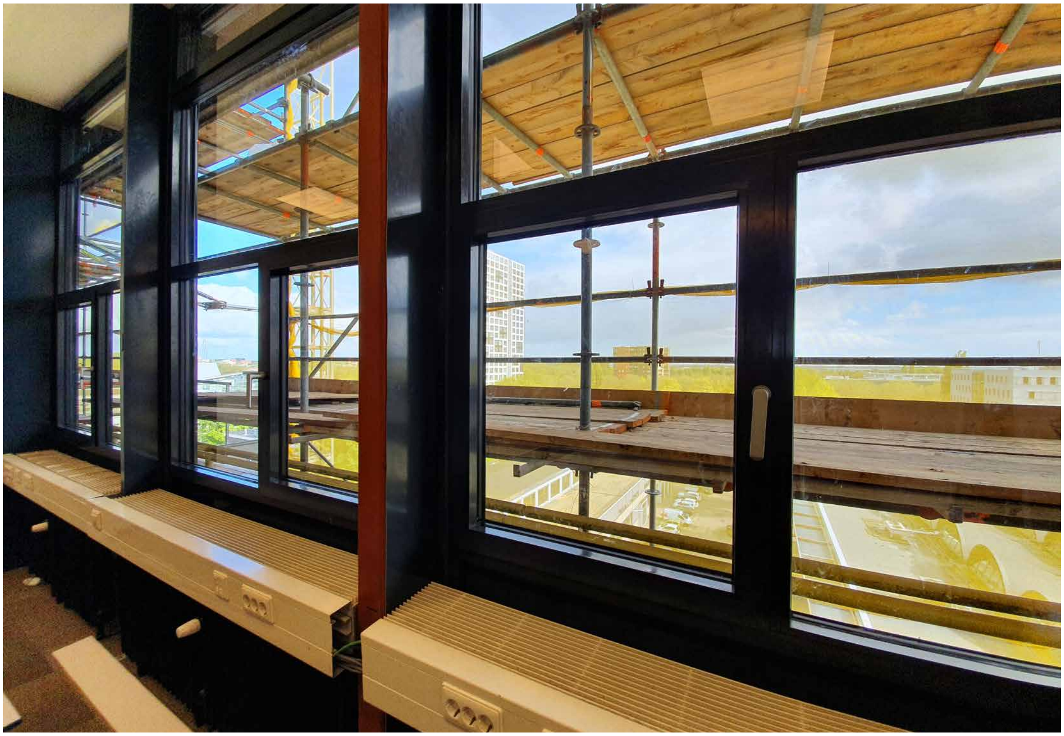

FIG. 5.1 Interior photograph of the FaaS façade renovation at the CiTG faculty building large-scale demonstrator prototype, at TU Delft, in the Netherlands. (Photo: Azcárate-Aguerre, 2019)

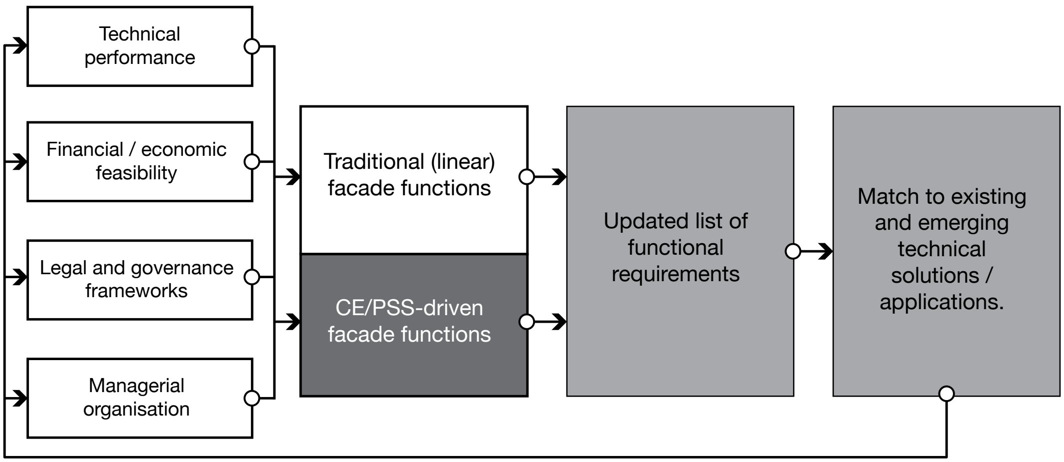

FIG. 5.2 Research-through-design feedback loop in the multi-stakeholder co-creation process of the two façade leasing (FaaS) prototypes.

The study was carried out in an iterative feedback process bridging supply and demand, academy and industry. Due to the innovative and explorative nature of the Facades-as-a-Service model few references could be found beforehand to determine the exact technical and organisational challenges that would be faced in practice, or the entire range of technical solutions which would be needed to address these challenges. The research consortia, therefore, approached the problem as a practical engineering and business modelling process, testing the system through real-life case-study projects and implementing diverse façade-related technologies as specific and unexpected challenges related to the FaaS model implementation and operation emerged. These iterative technical development steps, and their relevance to a circular façade economy, are reviewed and structured in a FaaS development matrix.

5.4 Results

Results are structured in accordance with the outcome of each methodological step:

5.4.1 Literature Summary

Based on literature references, two development paths are recognized as potentially leading to enhanced material circularity (CE-path) and servitisation of product manufacturers (PSS-path). These two complimentary paths constitute the strategic innovation direction for technological development in order to enable the CE and PSS transitions in the façade industry through specific and targeted steps:

CE path (the Y-axis): The key reference to establishing a clear theoretical framework for circular technological development are obtained (From Potting et al., 2017; RLI, 2015). These sources propose three strategic paths: (A) smarter product use and manufacturing, (B) extend lifespan of product and its parts, and (C) useful (end-of-service) application of materials. The source also allocates ten “R” strategies to deal with materials and products and deliver the strategic goals (A to C mentioned above), see Table 5.1.

PSS path (the x-axis): Theory on the path followed by product manufacturers in their transitions towards service providers is obtained from Baines and Lightfoot (T. Baines & H. Lightfoot, 2013; T. Baines & Lightfoot, 2014). In these sources the authors recognise and organise the incremental approach through which linear product manufacturers-whose role traditionally ends at the front-sales office-can gradually shift towards more integral performance-based contracts. Such contracts will enable them to retain responsibility (and in some cases also legal and economic ownership) over their products, while deriving long-term value from the service component and from the performance results delivered by these physical and digital products to their end customers. The steps along this process are identified as: (1) basic supply services such as the delivery of products and spare parts; (2) intermediate services involving the repair, overhaul, monitoring, and maintenance of the products; and (3) advanced services such as rental agreements, risk and revenue sharing, and revenue through use, Table 5.2.

TABLE 5.1 Circular strategies within the production chain, in order of priority.

Building Phase	Produce				Construct			Use		End-of-Service
Circular strategy	Smart use and Manufacture				Extended lifespan					End-of-Service appl.
“R” Strategy	R0. Refuse	R1. Rethink	R2. Reduce	R3. Reuse	R4. Repair	R5. Refurbish	R6. Re-manufacture	R7. Re-purpose	R8. Recycle	R9. Recover

Adapted and summarised from Potting et al. (Potting et al., 2017)

TABLE 5.2 Incremental servitisation process.

Servitisation Level	Basic Services		Intermediate Services						Advanced Services			
PSS phase	Supply		Repair		Maintain					Operate		
Tasks	Supply product	Supply spare parts	Help-desk	Repair	Overhaul	Scheduled maintenance	Condition monitoring	Field services	Customer support agreement	Rental agreement	Risk and revenue sharing	Revenue through use

Adapted from Baines & Lightfoot (T. Baines & H. Lightfoot, 2013)

5.4.2 Defining a Technological Development Matrix for New Stakeholder Circular Services in a Façade-as-a-Service System

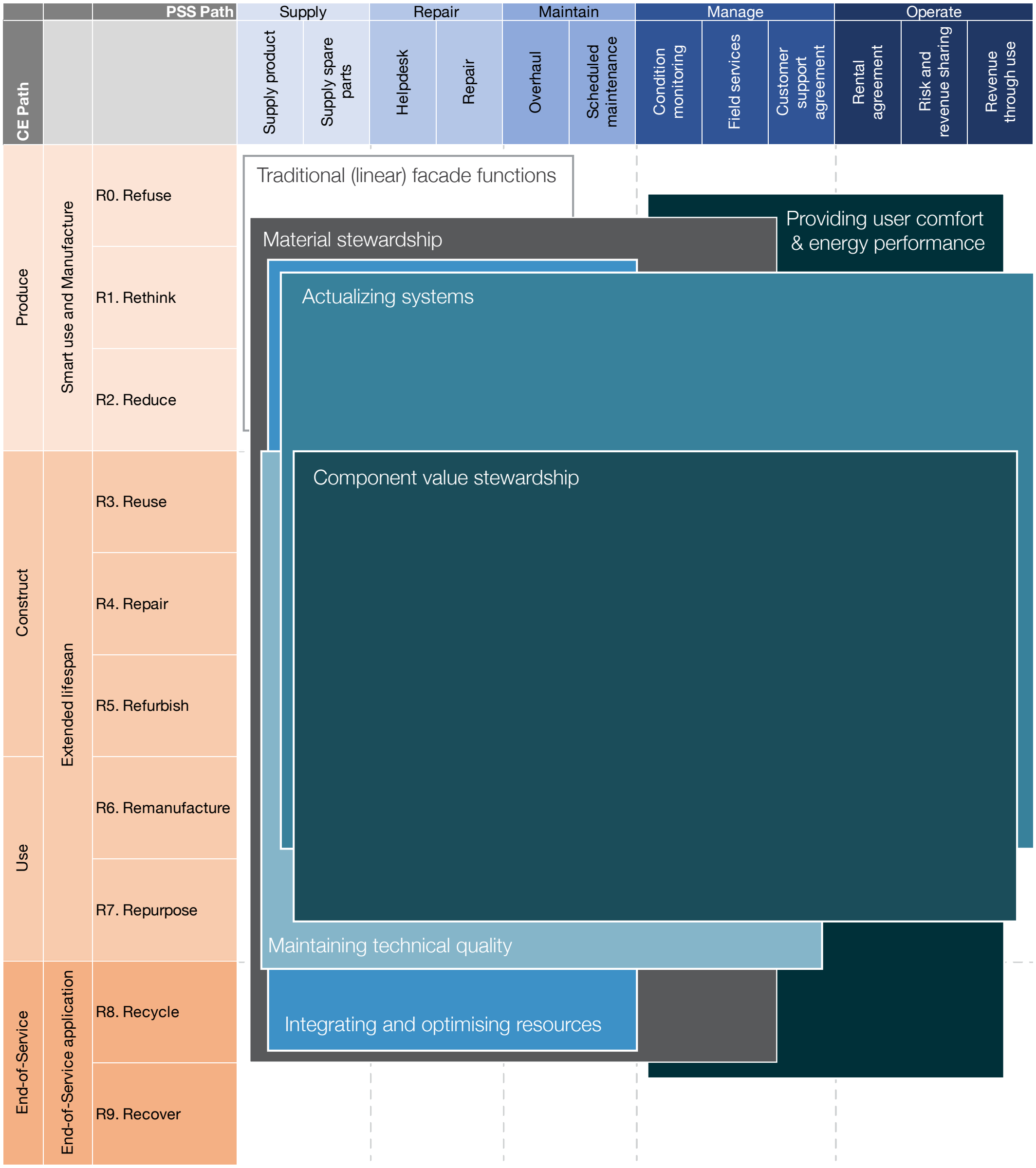

FIG. 5.3 General fields of circular services enabled by a facades-as-a-service model.

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The “FaaS technological matrix” (see Figure 5.3) is the result of the intersection between performance contracting objectives and material circularity objectives. Traditional (linear) façade functions (Klein, 2013), can be located in the top-left corner of the matrix, as they: (A) deal mostly with the production phase in terms of circular economy strategy, offering limited opportunities for high value recovery or reprocessing; and (B) deal mostly with the product-system end of the PSS spectrum. In other words, the delivery of products and replacement of certain components, but generally without extended customer service, system upgrading, performance delivery, or value co-creation intentions.

As a first step, the matrix is used to organise the *circular services* demanded and delivered by the diverse consortium stakeholders, and therefore, provide a structure on which to map the more specific functional requirements and technical solutions. The purpose of this list is not to be exhaustive, as no present methodology would allow the creation of an exhaustive list of all possible functional requirements nor technical solutions. Rather, the purpose of the list is to provide an overarching framework for the future development and/or application of building technologies. This framework is based not on gradual innovation and incremental improvement in a largely commoditised façade technologies market, but rather on the fulfilment of specific circularity- and sustainability-oriented service-delivery objectives as part of a collaborative and integral long-term value proposition.

5.4.3 Functional Requirements and Technical Solutions in the Transition to a Circular, Performance-Based Façade Industry. Lessons Learnt from the EWI and CiTG Pilot Projects.

New functional requirements can be arranged along the PSS and CE paths on the matrix, resulting in a graphic impression of the scope of action enabled by each technology along both (interrelated) development paths. A breakdown of selected circular and performance-based functional requirements is shown in Figure 5.4, below. Examples of technical solutions addressing these technical requirements are shown to the right of the figure.

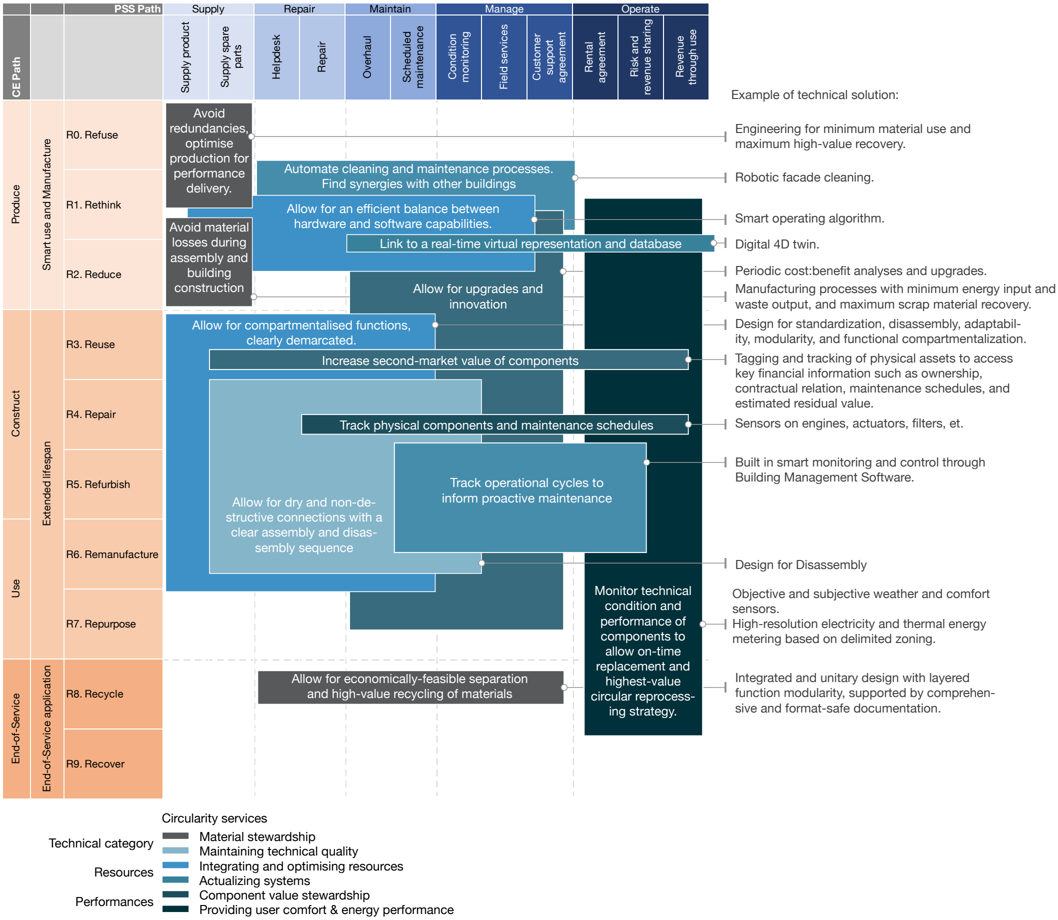

FIG. 5.4 Selected new circularity-enabling façade functional requirements mapped according to the CE/PSS paths of the FaaS technological matrix. Examples of technical solutions to address these functional requirements are shown on the right.

The selected requirements and solutions illustrated above have been either implemented or considered for implementation in the two FaaS pilot projects. In some cases, the specific solution could not be implemented due to real-life constraints such as project budget, delivery timeframes, or full technological readiness. The technological readiness level (TRL) of most necessary façade-integrated technologies is high. In many cases, however, market-ready technologies are failing to reach full-scale market adoption due to a lack of demand or need for such technologies in a traditional procurement process.

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The conceptualization of circular and performance-based functional requirements, not only during the early product development and project planning phases but throughout the building's service life, aims to solve the increasing issue of green-washing and circularity-washing in the construction sector. Within such a framework component manufacturers and suppliers should not limit their arguably circular offerings to products designed for disassembly or manufactured out of bio-based materials, but rather need to show proof that their product/service offering enables and aligns with the advanced functional requirements of the PSS and CE transitions throughout their operational lives.

5.5 Discussion

The innovative approach of this study is to propose a strategic path for the development of technical solutions to a new set of functional requirements as established by the economic and managerial priorities and demands of the diverse stakeholders involved in a potentially circular FaaS model contract. If diverse stakeholders are responsible for guaranteeing the ongoing performance of a façade over decades, then a new set of functional requirements is needed in order to reduce uncertainty and risk while monitoring actual delivered performance.

The outcome of this research is a strategic approach to the development of façade--integrated technologies, engineering and manufacturing processes, and asset management systems. These new practices must align with financially feasible material circularity and energy efficiency goals. Currently, the building industry in general and the façade industry specifically are characterised by a large number of small to medium enterprises working on different levels of gradual technological innovation and improvement. In terms of energy performance, the incremental improvement provided by better insulation or slightly more efficient heating and cooling systems has been increasingly encountering the economic law of diminishing returns (Cianfrone, Roppel, & Hardock, 2016; Hernandez & Kenny, 2011; Nowakowski & Hahn, 2013). Such diminishing returns become even more apparent when one considers the increasing value of larger volumes- or diversity-of material resources embedded in products, or the use of rare earth metals and other critical materials which are subject to limited global supply while crucial in the manufacturing of clean energy and smart building technologies (Abraham, 2015; Friege, 2012; Haxel, 2002; Lampropoulos et al., 2020; Meyer, Peck, & Bähre, 2018; Pitron, 2020; Vidal-Legaz et al., 2016). Global supply-chain pressures, rising commodities markets, and volatile energy prices exacerbated by the COVID-19 pandemic have highlighted the fragility of material and component sourcing networks across all industries (Ezeaku, Asongu, & Nnanna, 2021; Priya, Cuce, & Sudhakar, 2021). This is in turn leading to broader conscience among product manufacturers regarding the long-term financial and strategic cost of neglecting recovery of their material resources and re-manufacturable cores (Hazen, Russo, Confente, & Pellathy, 2021; Opresnik & Taisch, 2015; Toffel, 2003).

A technological development path based on a transition towards façade servitisation represents a radical rethink of the economic incentive and decision-making processes which currently dominate the façade and construction industries. A shared long-term view of physical and digital building technologies aimed at maximising performance delivery provides the façade industry with a shared goal (and challenge) beyond that of competing among highly commoditised products and services with marginal technical distinctions. The technological implementation fields resultant from this study should not be seen as an exhaustive list of all components needed for an effective facades-as-a-service model, but rather as a strategic model according to which new technologies can be organised to meet actual value-chain challenges through technologies which are justified from-and required by-a whole multi-life-cycle perspective. The research demonstrates the relevance of collaborative systemic development and value creation by involving all relevant stakeholders from the earliest planning phases. This aligns with the process described by other sources, in which functional requirements and technological readiness provide a starting point and practical dimension to the iterative process of co-designing a PSS offering (Huizing et al., 2019; Orellano, Medini, Lambey-Checchin, & Neubert, 2019; Ruvald et al., 2019)

Lastly, the paper highlights the relevance of a new way of understanding building procurement. The current one-way supply-chain in which all components are installed in order to fulfil demand-side needs or regulatory safety and health requirements, limits economic interest and financial investment from other stakeholders. New façade functionalities, such as design for disassembly or tracking of embodied components and materials, are not (yet) required in the interest of the client or regulators, but in the interest of the service provider whose components will benefit from a higher and more predictable residual value. Investment in such technical solutions, which are likely to increase the initial cost of CE- and PSS-enabled façades, must therefore be borne by the service provider or by the system's financiers in a shared co-investment and co-benefiting model.

5.6 Conclusions

The objective of this paper has been to outline a technological development path for façades and façade-integrated systems, in line with the changing requirements of the circular economy and product–service systems transitions. In other words, a system for understanding and organising those new façade functionalities which might enable the feasibility and effectiveness of a FaaS contract.

Finding that existing technologies and emerging applications are enablers of PSS and a CE, our conclusions are that suppliers of building technologies aiming to engage in servitisation of their activities must extend their front-office operations from the sale of products to the ongoing delivery of measurable performance indicators. This transition significantly-though by no means solely-relies on technological innovation and integration.

Technical innovation targeting incremental improvement of component performance has so far often failed to reach mainstream implementation due to economic, social, political, or managerial barriers. The research-by-design process followed by this study and paper has exposed economic and contractual challenges such as profitability, risk distribution, legal demarcation, and performance monitoring, exacerbated by the long time-scale of building projects, as key to the implementation of PSS models. Such models are, in turn, likely to safeguard CE objectives throughout the building's life cycle.

The systemic change introduced by the adoption of the technologies presented in this paper aims to align technological progress with a strategic view of CE and PSS goals. Such a perspective is expected to increase the chances of energy-efficient technologies achieving a wider market impact without resulting in a further increase in resource consumption and environmental degradation.

Chapter conclusions

The chapter has concluded that integrated façade technologies are generally in a mature stage of development and are for the most part ready to deliver extensive (if not yet full energy- and comfort-inclusive) performance contracts.

It proposes that development of façade-integrated technologies should follow a more strategic path towards service delivery, by understanding the needs not only of the building's end-user, but also of the service providers, facility managers, maintenance crews, financiers, and other stakeholder with an active, ongoing, and long-term interest in the building's performance. It also proposes that integration of the different façade-integrated technologies is in the interest of different stakeholders, and should therefore be financed in a collaborative way instead of simply passing all costs on to the building owner/end-user.

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6 The financial dimension

A “Total Value of Ownership” model to support deep building energy renovations

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ABSTRACT The regulatory drive to accelerate the clean energy and circular economy transitions in the European building stock is currently failing to overcome systemic implementation barriers. These barriers include high initial investment costs, misaligned financial incentives among stakeholders, and the relatively low cost of less sustainable energy and materials. A Product-Service Systems (PSS) approach could successfully overcome many of these barriers by (1) outsourcing capital investment, as well as financial and technical risks, (2) providing shared economic incentives to collaborating stakeholders, and (3) retaining extended producer responsibility and ownership over materials and products. However, PSS is still not seen as a viable business model when compared to both a standard “ownership” contract and a “no-retrofit” scenario. This paper proposes a Total Value of Ownership (TVO) method to evaluate the financial performance of a building energy retrofit in terms of Net Present Value, comparing a matrix of scenarios. Results show that – when accounting for capital and opportunity costs tied to alternative investments, internalising externalities, and monetising soft values such as user productivity and property value – a PSS model can deliver the highest NPV. Furthermore, results show that a PSS alternative can act as a positive future-proofing strategy to safeguard the building owner’s position in the face of uncertain future market indicators and carbon taxation. Recommendations for policymakers,

investors, financiers, building owners, and end-users are presented to identify the economic value of PSS contracts, leading to better-informed decisions which can accelerate deep energy retrofit of the building stock.

Chapter summary

As concluded in *Chapter 4. Drivers and barriers to the delivery of integrated Facades-as-a-Service*, the financial and economic feasibility of a Façades-as-a-Service model relies partly on an accurate methodology for assessing the overall value it can provide to building users and operators (clients), investors, and other financiers. This chapter describes the development of a comprehensive matrix for calculating Total Value of Ownership for a performance-based façade contracting project by focusing on the microeconomics of FaaS evaluation.

Microeconomics is the field of economics concerned with the study of decision-making by individuals and companies regarding the investment of scarce resources, as well as the effects of such decisions (Frank, 2010). The strategic priorities and economic incentives of real estate developers and managers largely define the type of choices they are likely to make. A series of factors contribute to decision-making in the real estate sector becoming increasingly complex, such as: Technical diversity and intricacy of building systems, project scale (both spatial and in time), interdependent cross-disciplinary planning and execution mechanisms, and ever-faster changes in user trends and regulatory technical requirements such as safety, comfort, and energy performance. All these factors are exacerbated by the relatively long construction and operational phases of a building project, the former frequently taking close to a decade, while the latter often spans one or more human generations. The preservation of real estate value – in both financial and social-utility terms – at the heart of the real estate management discipline, relies on the future-proofing of projects and portfolios against future uncertainties. Such risks can be internal or external to the project.

Economic and environmental analysis tools – such as LCA and LCCA – aim to support decision-making between technical alternatives by exposing the direct financial and environmental impact of certain decisions during the project's construction and operational phases. Financial analysis tools, such as Return on Investment (RoI) and Internal Rate of Return (IRR) calculations, support decision-making between different investment alternatives, by balancing total project expenses against total project revenue over a determined timespan. These traditional methods most often focus on direct and project-specific factors such as, for example, cost of energy retrofit versus operational energy savings. Such a focus often excludes less tangible sources of value and indirect financial incentives (or deterrents), which could play an even larger role on the initial building or retrofitting decision (BPIE, 2013, p. 12). In other words, while traditional LC(C)A and IRR methods help us decide a course of action in terms of hard expenses and incomes, an extended methodology is needed to qualitatively evaluate the extended soft impact such decisions can have for the organisation, the environment, and the local and global societies.

This chapter aims to develop the foundations for a fair methodology which integrates soft values and costs, as well as specific externalities, into the building envelope investment evaluation process.

6.1 Motivation, context, and background

6.1.1 The relevance of building de-carbonisation

In 2018, the European Commission (EC) published a communication confirming "Europe's commitment to lead in global climate action, and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition and in a cost-effective manner" (European Commission, 2018). In March 2020, the EC presented a proposal to enshrine the 2050 carbon neutrality target for the EU into law (European Commission, 2020). The expected contribution to this target from the construction and infrastructure industry is framed in the EU Clean Energy Package and in the EU Circular Economy Package:

The EU Clean Energy package requires member states to prepare national policy measures to achieve high renovation rates, smart and de-carbonised buildings with reduced energy consumption, and supplied with renewable energy sources (European Commission, 12 March 2020).

The EU Circular Economy Package, adopted in March 2019 in its 4th version, states the aims of maintaining the value of products and materials for as long as possible, minimise waste and resources use, and use products again after they reach their "end-of-life" to create further value (European Commission, 4 March 2019).

Approximately 800 million tonnes of partially recyclable and reusable construction and demolition waste are generated every year (European Commission, 9 August 2019), but the challenge of whole life cycle building de-carbonisation in Europe mainly concerns the 25 billion m^2 of usable floor space that has already been built. As is well known, renovation rates have consistently remained below target (Economidou et al., 2011), while the average share of renewable energy supplied to buildings in the European Union remains around 20% (Eurostat, 2021).

6.1.2 Barriers & opportunities

Extensive literature has validated that existing buildings can reach net carbon neutrality through the use of market-ready, affordable technologies, both from the point of view of embodied as well as operational carbon (Almeida & Ferreira, 2017; Conci, Konstantinou, van den Dobbelsteen, & Schneider, 2019; Ferreira, Almeida, Rodrigues, & Silva, 2016; Lannon, Georgakaki, & Macdonald, 2013; Xing, Hewitt, & Griffiths, 2011). Common strategies include the use of biomass (i.e. timber) as construction material, combined with highly insulating envelopes, energy-efficient thermal energy systems (such as heat pumps), and renewable energy generation (such as photovoltaic cells).

Despite available technologies, demand for both retrofitted and new carbon neutral buildings is low. Extensive interviews and surveys among individual stakeholders have identified two main barriers to deep energy retrofits: a lack of access to initial capital, and conflicting incentives in how to invest it (Azcárate-Aguerre, Konstantinou, et al., 2017; Build UP | Webinar on Putting EU Green Deal in Action, 21 April 2020).

Long-term property assessed clean-energy (PACE) investment funds, which pre-finance renovation measures with guaranteed pay back from energy savings (www.europace2020.eu) have been developed to incentivise building owners and occupiers to invest in building de-carbonisation by offsetting initial capital needs. This approach resulted in the successful large-scale deep energy renovations of up to 10,000 apartments at a time (Energiesprong, 6 December 2019), but a challenge often encountered is that initial capital costs are not compensated over the project's service life, resulting in a net loss for the investor. This can be due to market forces and/or regulation (e.g. regulatory limits on rental prices or markets with fluctuating valuation of energy labels and other performance certificates (Holtermans & Kok, 2019)); due to split incentives (e.g. when landlords pay for the renovation but tenants pay for operational energy costs (Melvin, 2018); or because energy cost savings fail to materialise to the required extent (e.g. user rebound effect (Bourrelle, 2014)).

Reaching carbon neutrality in real estate projects also adds a layer of complexity to the already time-consuming decision-making structure of building renovations: few building professionals have the skills to plan and deliver a carbon-neutral building, and few clients are willing or equipped to contextualise and assess the additional evaluation criteria. This additional effort is not monetisable as real estate valuation processes do not – at present – fully or reliably account for the value of sustainability, neither in terms of energy consumption nor of material circularity (Rooplal Utmani, 2021; Warren-Myers, 2013). Several EU-funded projects such as (Eenvest, 2019–2020; Launch, 2019–2020; TripleA-reno, 2018–2021) aim to accelerate the demand for deep energy renovations. They focus on the investor and building owner's perspective by addressing capitalisation, added-value standardisation, and user-acceptance barriers.

As recognised by the EC, circular strategies can generate new revenue streams, because circularity hinges on closing material loops – i.e. the secondary revalorisation of the stock – which means that "waste" materials and components are turned into new products at the end of (each of) their service lives ((At. Ajayebi et al., 2019; A. Ajayebi et al., 2020; Alhola, Salmenperä, Ryding, & Busch, 2017; City of Helsinki, 2019; Hopkinson, Chen, Zhou, Wang, & Lam, 2018). This should improve on the financial balance of net-zero carbon buildings. This potential new revenue stream, however, has so far not motivated a large uptake in this kind of projects, mainly due to the fact that the market for secondary material streams is not yet mature or predictable, rendering the long-term value trend of such components and materials uncertain.

Policy could help, first and foremost by regulating negative externalities, such as carbon emissions, on the grounds of being a societal hazard and a threat to the well-being of present and future generations. Another important step could be to invest public funds in increasing construction professionals' skills and capabilities in delivering carbon neutral buildings, for example in planning and building with wood, designing for disassembly, re-manufacturing, carbon accounting, and cost-benefit analysis tied to Environmental and Sustainability Goals (ESG) credit ratings. A notable actor in this area of work is the Ex'tax Foundation (www.ex-tax.com), which is helping countries to pioneer these approaches. Yet another promising policy shift – more radical but which is gaining traction – is an increase in taxation of material resources and a decrease in taxation of human labour (Milios, 2021; W.R. Stahel & Clift, 2016). This measure could significantly improve the financial case for material resource recovery in advanced economies where the cost of labour is a significant barrier to effective material circularity (Matsumoto, Yang, Martinsen, & Kainuma, 2016; Milios, Beqiri, Whalen, & Jelonek, 2019).

There is thus a clear need for a collaborative approach that aligns levers of technology, finance and economics, and policy and regulation. Having established the role of technology and assuming policy will move slowly, we now focus on the economic and financial levers, which could be activated through a Product-Service System approach.

6.1.3 Product-Service Systems: a potential energy-retrofitting catalyst

Product-Service Systems (PSS) are a category of business models which aim to shift the focus of value in economic transactions away from that of tangible material products, and towards that of the intangible functional performance delivered by these products. PSS could act as a catalyst of deep building energy renovations, as illustrated in Figure 6.1, by:

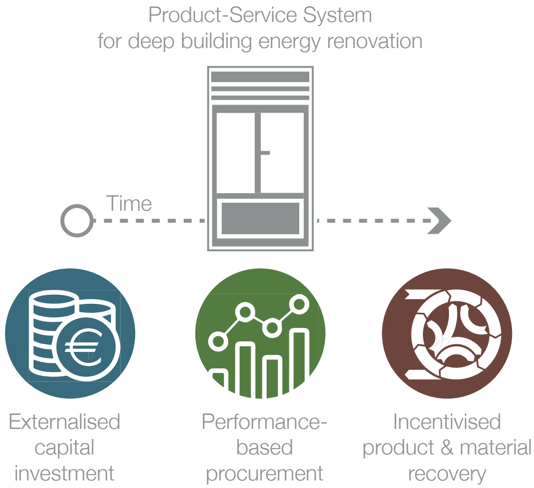

FIG. 6.1 Three aspects of Product-Service Systems that could potentially accelerate the deep energy renovation of the built environment while enabling product and material circularity.

- **Offsetting** the initial investment to an external financing party, therefore unlocking access to external capital while avoiding internal opportunity costs;
- **Tying** long-term performance-based contracts to bespoke sets of indicators, like comfort and environmental impact, so that externalities and co-benefits can be effectively monetised; and
- **Retaining** materials ownership with the supplier (or supplier consortium), who is responsible for their performance. Thus incentivising durability, repairability, and the recovery of residual value at the end of components' service-lives – i.e. a circular use of resources.

PSS is not a new concept in the construction and real estate management fields. Its overarching value proposition, organisational implications, and sustainability potential have been recognised for over two decades (Leiringer & Bröchner, 2010). Numerous authors have identified and highlighted a natural alignment between PSS, the Circular Economy, and environmental sustainability (Mont, 2002; W.R Stahel, 1997; Vezzoli et al., 2013). Nearly twenty years later, an increasingly mainstream interest in the Circular Economy has brought the concept of PSS to the foreground of a broader societal and industrial debate, at least in the Northwestern European context.

Three main uncertainties regarding the applicability and feasibility of PSS have been identified to date: the readiness of companies to adopt them, the readiness of consumers to accept them, and their environmental implications (Mont, 2002). A challenge to its wider implementation has been recognised as the lack of quantitative tools to determine the total value delivered by PSS offerings (T. S. Baines et al., 2007; Wang et al., 2011). These uncertainties and challenges remain largely unsolved: suppliers are still mostly reluctant to invest resources in a transition for which there is still no widespread demand; consumers lack the tools to determine whether a PSS alternative is beneficial to them beyond the initial investment and; environmental benefits remain largely untested as few companies have implemented PSS, and those which have rarely publish specific information on its mid- to long-term financial and environmental results.

In the last 10–15 years a small number of authors have proposed economic evaluation methodologies for the development and implementation of different PSS models.

These analyses have been characterised as: (a) highly specific to their regional or sectoral context, with limited transferability to other contexts; (b) mostly reliant on individual case-studies, or a small sample thereof; and (c) largely focussed on abstract sources of customer added value (i.e. soft values) rather than hard monetised performance evaluation (Reim, Parida, & Örtqvist, 2015; Joris Van Ostaeyen, 2014).

Several methodologies have focussed on supply-side readiness by proposing methods for evaluating PSS-related cost-savings potential for the manufacturer and service provider. They found that PSS savings could theoretically result in optimised commissioning costs to the customer, however, suppliers have also been rated as not always ready to reap such savings (Lind & Borg, 2010; Straub, 2010; J. Van Ostaeyen, Kellens, Van Horenbeek, & Duflou, 2013).

This paper focuses instead on the demand-side readiness by proposing a method for evaluating PSS-related cost savings potential for the commercial real estate owner and investor. Commercial building owners are defined as those for whom the ownership and exploitation of real estate represents the core business, as opposed to public or corporate real estate owners for whom the building acts as an operating asset to facilitate and enable their core processes and/or value creation activities. The method aims at supporting decision-making among both technological and contracting alternatives by providing an evaluation of Total Value of Ownership (TVO) in terms of Net Present Value (NPV) over a specific time frame for different building energy retrofit scenarios. A TVO analysis allows the assessment of specific impacts tied to a PSS approach thanks to the inclusion of the whole life cycle time-frame as well as “soft” values and co-benefits. Net Present Value allows for the evaluation of uncertain future developments through a sensitivity analysis, overcoming the barriers of traditional Life Cycle Costing (LCC) methodologies when dealing with factors such as the (future) value of sustainability, externalities, subjective strategic fit, and split ownership (Gluch & Baumann, 2004; Goh & Sun, 2016).

6.2 Method and materials

6.2.1 Design and structure to test the hypothesis: Product-Service Systems have the potential to unlock financing for building de-carbonisation

The study is structured in three steps:

1. Develop a TVO-based evaluation methodology to compare a PSS energy retrofitting contracting solution against alternative contracting scenarios. We will subdivide the evaluation into a TVO subtotal including only “hard” monetary values and a TVO + total including selected “soft” values as well.

2. Statistically test this methodology using an archetypal retrofit project based on industry-average data for the Dutch commercial real estate and construction sectors. The use of a statistical model, rather than a (selection of) case-study building(s), aims to ensure our results are as broad and representative as possible, and not determined by the specific project and client characteristics of the selected sample.

3. Perform a dynamic sensitivity analysis through a Monte Carlo simulation to determine the extent to which the different parameters influence the financial investment performance of the TVO+. The parameters are selected as a combination of the most determinant ones in the archetypal static analysis and the most widely ranged for different investor profiles (private, corporate, public).

6.2.2 TVO-based evaluation methodology

Total Value of Ownership (TVO) is the sum of a project's total costs and its total value, including capital expenses, such as initial investment in year zero and opportunity costs, and indexed future cash flows over each planned year of operation (Davis, Coony, Gould, & Daly, 2005; Joris Van Ostaeyen, 2014), but also other tangible and intangible factors as determined by the decision-maker. The scenario with the highest TVO is the most financially attractive, for the investor who needs to choose between alternative projects which offer equivalent utility performance.

A basic approach to the most tangible TVO factors is thus determined by the formula:

$TVO = -P_x - O_x - M_x - E_x + T_v + R_v TVO = -P_x - O_x - M_x - E_x + T_v + R_v$

Where:

P_x is the capital cost of the project's **initial investment in €/m² NFA** plus the region's bank loan servicing cost

O_x is the **opportunity cost of capital** for the project's initial investment in €/m² NFA at the region's Weighted Average Cost of Capital (WACC)

M_x are the **indexed future maintenance costs** SUM of M_1, M_2, M_3,…M_x in €/m² NFA, plus the cost of deferred maintenance in a no-renovation scenario.

E_x are the **indexed future energy costs** SUM of E_1, E_2, E_3,…E_x in €/m² NFA

R_v is the **indexed value of rental revenue** SUM of R_1, R_2, R_3,…R_x in €/m² NFA

T_v is the **indexed transactional value of property appreciation** SUM of T_1, T_2, T_3,…T_x in €/m² NFA

The extended approach including softer or less tangible indicators of value, proposed by this study as TVO+analysis, is determined by the formula:

$TVO+=TVO-S_x-H_x TVO+=TVO-S_x-H_x$

Where:

S_x are the **indexed shadow carbon costs** SUM of S_1, S_2, S_3,…S_x in €/m² NFA

H_x are the **indexed costs of a decrease in staff productivity** due to poor indoor comfort, SUM of H_1, H_2, H_3,…H_x in €/m² NFA

C_v is the **indexed material or components value recovered** through, respectively, recycling or re-manufacturing activities, in % of original component value indexed at the end of service life.

We use the TVO and TVO + formulas to evaluate the following matrix: a "Business-as-Usual" (BaU) scenario, in which no energy renovation takes place, and a de-carbonised "Net-Zero" building energy retrofit project, financed either through a standard ownership contract, or through a PSS contract (see Table 6.1):

TABLE 6.1 Matrix of analysed scenarios for TVO and TVO+ evaluation.

Project options	'Business-As-Usual' Building (no intervention)	Net zero carbon Building (after retrofit)	Net zero carbon Building (after retrofit)
Ownership financing	Ownership financing	Ownership financing	PSS financing

6.2.3 Parameters and boundary conditions for selected archetypal case-study

In this section we summarise and justify boundary conditions as well as our selection of values to apply the TVO-based evaluation method to an archetypal case-study project.

Boundary conditions – geography

The range of financial parameter values central to this calculation varies across European countries without a recognisable reciprocal trend. Notably these financial parameters are the Weighted Average Cost of Capital (WACC), which is the average cost of debt (bank loans) and equity (investor's capital) for commercial projects, and labour costs. Both influence initial investment, opportunity costs, and maintenance costs. For this reason, we selected the Netherlands as a proxy for a Northwestern European country-average evaluation, due to its comparable climate, socioeconomic, and financial indicators (Stein, 2016), as well as its solid databases documenting building stock and market prices. To note is that WACC averaged 6.3% in the Netherlands and 7.3% in the EU-28 as per the results of the Intelligent Energy – Europe project's DIA-CORE (Ortner, Welisch, Busch, & Resch, 2016).

Boundary conditions – time

We perform the quantitative evaluation of Total Value of Ownership (TVO) over the next 30 years to align the analysis with the EU-wide target of carbon neutrality by 2050.

Parameters – initial investment and opportunity cost

Table 6.2. summarises Initial investment and opportunity costs parameters. To note is that for the analysis presented in this paper we select an average existing non-residential building, a category that comprises 39.3% of Dutch building stock (European Commission, 6 April 2021) and has an average area of 2.000 m^2 (BPIE, 2011; Sipma, 2019).

TABLE 6.2 Initial investment and opportunity costs parameters.

	Parameter	Functional Unit	BaU	Retrofit (ownership)	Retrofit (PSS)	Source
	EPC label	Grade	E	A	A	Arcipowska et al. 2014
	Primary Energy use	kWh/ m2 NFA/a	265.00	50.00	50.00	(Filippidou, Nieboer, & Visscher, 2017)
	Net floor area	NFA	2.000	2.000	2.000	
	Planning & PM (15% of construction)	€/m2 NFA	N/A	–€ 52.05	–€ 52.05	
	Façade retrofit	€/m2 NFA	N/A	–€ 128.00	–€ 128.00	COBOUW, 2020
	Heat pump energy system retrofit	€/m2 NFA	N/A	–€ 219.00	–€ 219.00	COBOUW, 2020
	Depreciation over 30 years	%	100%	100%	70%	
Px/Ox	Initial investment	€	N/A	-€ 399,00	-€ 399,00	
	Asset-backed loan (mortgage) index (10-year fixed)	%	1.60%	1.60%	1.60%	https://www.hypotheekvisie.nl/hypotheek-berekenen/hypotheekrente-vergelijken
	WACC commercial sector	%	6.30%	6.30%	6.30%	(Ortner et al., 2016)

Initial investment costs include planning and project management, materials and components, installations, and construction costs, all including Dutch 21% VAT. For the renovation, we use the Energy Performance Certificate (EPC) label – a rating scheme to evaluate the energy efficiency of buildings in the European

Union (Arcipowska et al. 2014) – to characterise a building's energy-relevant physical characteristics. EPC labels range from G, the lowest, to A, the highest and most energy efficient. According to Zebra2020 Data Tool by Enerdata the most common EPC label for non-residential buildings in the Netherlands is label "E," comprising 35% of the building stock. This value is consistent with the average for the 9 European countries providing data. An EPC label "E" translates to a primary energy consumption for heating and Domestic Hot Water preparation of 265 kWh/m^2/year (Filippidou et al., 2017). In buildings with EPC label "E," thermal energy is usually generated through boilers running on natural gas. An EPC label "A" building, in contrast, has a primary energy consumption for heating and Domestic Hot Water preparation of <50 kWh/m^2/year thanks to an insulated façade and typically generated through a heat pump system, see Figure 6.2 (Engie.nl, 2021).

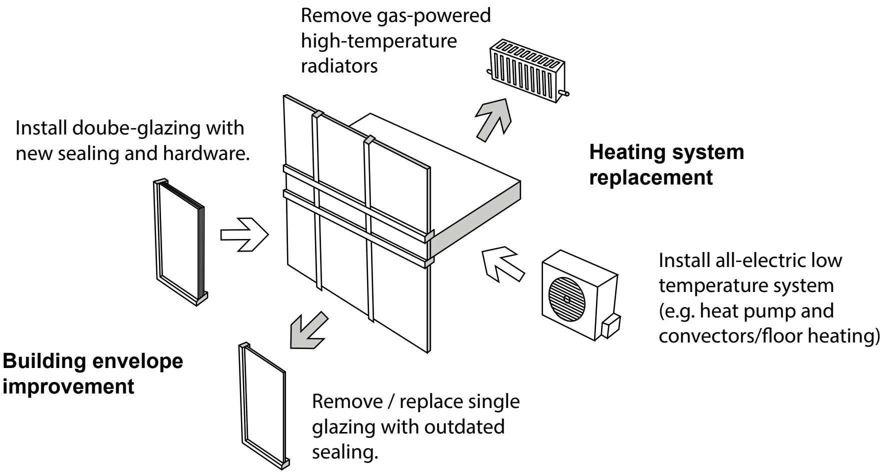

FIG. 6.2 Technical sketch of implemented deep energy retrofit measures on the archetypal building. The study is applied to a generic, archetypal building based on broad statistical data from the Dutch context in order to overcome the highly specific (and thus non-representative) values of any specific case-study project or sample of projects.

As defined by IEA Annexe 61 (Zhivov et al., 2017), a major building renovation project in which site energy use intensity has been reduced by at least 50% from the pre-renovation baseline is a "deep energy retrofit," so an improvement from EPC label "E" to "A" therefore represents a "deep renovation". We also include depreciation, which is tied to the service life of each component. For reference, EEFIG De-risking Energy Efficiency Projects (DEEP) Platform (https://deep.eefig.eu/) lists the initial investment to retrofit a non-residential building in the EU-28 at

€88/m² floor area for the building envelope and €198/m² floor area for the HVAC system, while data from 8 EU countries provided by Zebra2020 Data Tool results in an average investment costs of €430/m² for a "deep renovation" of a non-residential buildings, so that this case falls within a realistic range.

Parameters – indexed costs

Table 6.3. summarises Indexed parameters, which include maintenance costs, energy costs, rental value, and property value.

TABLE 6.3 Indexed parameters (including maintenance costs, energy costs, rental value, and property value).

	Parameter	Functional Unit	BaU	Retrofit (Ownership)	Retrofit (PSS)	Source
Mx	Maintenance	€/ m2 NFA/a	–€ 3.86	–€ 3.86	–€ 3.86	https://www.beheerenonderhoud-kosten.nl/welkom
	Inflation index (1997–2020 CPI)	%	1.88%	1.88%	1.88%	(CBS, 2018)
	Energy price	€/kWh	–€ 0.04	–€ 0.09	–€ 0.09	Eurostat 2021
	Gas index 30 years	%	1.90%	N/A	N/A	Cost Estimation tool by FROnT - Fair RHC
	Electricity index 30 years	%	N/A	1.40%	1.40%	Cost Estimation tool by FROnT - Fair RHC
Ex	Energy costs	€/m2/a	-€ 10.34	-€ 4.50	-€ 4.50	Zebra2020 Data Tool by Enerdata
	Gross rental income	€/ m2 NFA/a	€ 147,00	€ 161,00	€ 161,00	(ING Real Estate Finance, 2017)
	Rental price index Non-residential (XX years)	%	0%	2.50%	2.50%	(NVM Business, 2020)
	Property price		€ 1.235,00	€ 1.341,00	€ 1.341,00	(ING Real Estate Finance, 2017)
	Property price index Non-residential (XX years)	%	0.60%	0.60%	0.60%	(NVM Business, 2020)

To note is that the price of energy for non-household consumers in the Netherlands is €0.039/kWh for natural gas, with EU-28 average being €0.032/kWh (Eurostat, 2019b), and €0.09/kWh for electricity with EU-28 average being €0.12/kWh (Eurostat, 2019a). 4) We assume that the "green power" provider uses the same rates.

A study by ING Real Estate Finance and the University of Maastricht found that the Dutch real estate market grants a 9.9% rental premium and a 8.6% property value premium to an EPC label A building compared to the average building (ING Real Estate Finance, 2017). We use these factors to evaluate the potential increase in rental income and property value from improved EPC label for an average commercial property in the Netherlands, which has a gross rental income of €147/ m^2 NFA and a property value of €1.235/m^2 NFA.

Parameters – soft values

Table 6.4. summarises shadow carbon costs, staff productivity costs, and recovered material or components prices.

TABLE 6.4 Shadow carbon costs, staff productivity costs, and recovered material or components prices.

	Parameter	Functional unit	BaU	Retrofit (Ownership)	Retrofit (PSS)	Source
	Embodied CO2	kgCO2e/ m2/a	0.00	0.78	0.78	(Hildebrand, 2014)
	Operational CO2	kgCO2e/ m2/a	64.00	10.00	10.00	(Netherlands Enterprise Agency (RvO), 2017)
	Carbon credits price (EU ETS)	€/kgCO2e	–€ 0.03	–€ 0.03	–€ 0.03	(Carbon Pricing Dash-board, 21 March 2021)
Sx	Shadow carbon costs	€/m2/a	–€ 1.92	–€ 0.32	–€ 0.32	
	Shadow cost index	%			100 % until 2030. then tied to inflation	
	Average office employee brutto salary	€/year	-€ 41.300,00	-€ 41.300,00	-€ 41.300,00	https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83740NED/table?dl=1A6C1
	Average floor area per employee	m2	23	23	23	Buitelaar et al. 2017
	Productivity loss	%	2%	2%	2%	(Brager, 2013; Terrapin Bright Green, 2012)
Hx	Personnel costs	€/m2/year	–€ 35.91	–€ 35.91	–€ 35.91	
	High-grade recycling value	%	0%	10%	N/A	
	Re-manufacturing value	%	0%	0%	30%	
	London Metal Exchange index (1985–2020)	%/year	4.63%	4.63%	4.63%	(Tradingeconomics.com, 2021)
Cv	Material circularity value	€/m2	N/A	€ 34.70	€ 104.10	

For the embodied GHG emissions resulting from the energy retrofit of a non-residential building we take the average from a study evaluating a wide range of non-residential case-study buildings with wood, concrete, and metal façade constructions (Hildebrand, 2014). We assume a credit for the next life of the component (offsetting the carbon emissions from virgin material extraction) of −30% in the PSS scenario. The operational GHG emissions are calculated using the GHG emission factor for Dutch power 0.413 $kgCO_2e/kWh$ (Netherlands Enterprise Agency (RvO), 2017), but, assuming the utility sector plays its part, in 2050 our target electricity system is carbon neutral. The average GHG emissions factor for the electricity consumption of the building with EPC label "A" between 2020 and 2050 is therefore 0.206 $kgCO_2e/kWh$, resulting in yearly GHG emissions of 50 kWh/m^2 * 0.206 $kgCO_2e/KWh$ = 10 $kgCO_2e/m^2/yr$ over the 2020–2050 period. For reference, in the alternative case of a "green" power provider who can certify 100% electricity generation from renewable sources from the first year of operation. The carbon emissions of this scenario should therefore be accounted for using the factor for value-chain emissions for solar and wind power, which is 0.011 $kgCO_2e/kWh$, resulting in 0.6 $kgCO_2e/m^2/yr$.

The hard-monetary cost of poor indoor comfort, and its effect on personal health, well-being, and productivity, is the subject of much scientific debate. Estimates for economic losses resulting from staff absenteeism and presenteeism due to factors such as poor thermal comfort, insufficient lighting, poor air quality, are often in the range of 2–4% (Feige, Wallbaum, Janser, & Windlinger, 2013; Olesen, 2005; Seppänen & Fisk, 2006; Terrapin Bright Green, 2012). For this study we use a conservative 2% loss, calculated over the average yearly salary of a Dutch office worker.

The current lack of strong secondary material and component markets, and the unpreparedness of the construction value chain to presently reabsorb the residual value of end-of-service components effectively – through recycling or re-manufacturing activities – makes it difficult to project a monetary value for such recovery. Expecting such market failures to be corrected in the coming decades, because of both policy incentives and industry interest, we propose a worst-case 10% residual value of recycled materials – largely resulting from the long-term value increase trend observed in the London Metals Exchange index – and a best-case 30% value recovery for high-grade re-manufactured components. Current examples from other industries point to value recovery through effective re-manufacturing to be much higher than 30% (Santini et al., 2011).

6.3 Results

Results show that the Net Present Value (NPV) of the investment after 30 years in the Basic TVO model is highest for BAU, followed closely by PSS contracting, while it is negative for Ownership contracting retrofit. This result falls in line with – and explains – the observable low retrofitting rates across the EU. PSS contracting results in a positive NPV because the potential financial profit from an alternative capital investment (i.e. the opportunity value of an alternative and independent project) over-performs the retrofit expenses, even after accounting for the additional setup and financing costs resulting from the outsourcing of the project's capital investment, as well as from the long-term technical management.

In the TVO + model, accounting for soft costs, the overall NPV of the project for the building owner/investor, is lower but still positive when retrofitting through PSS contracting, almost unchanged compared to Basic TVO when retrofitting through the ownership model, and strongly negative when no intervention is made, see Figure 6.3.

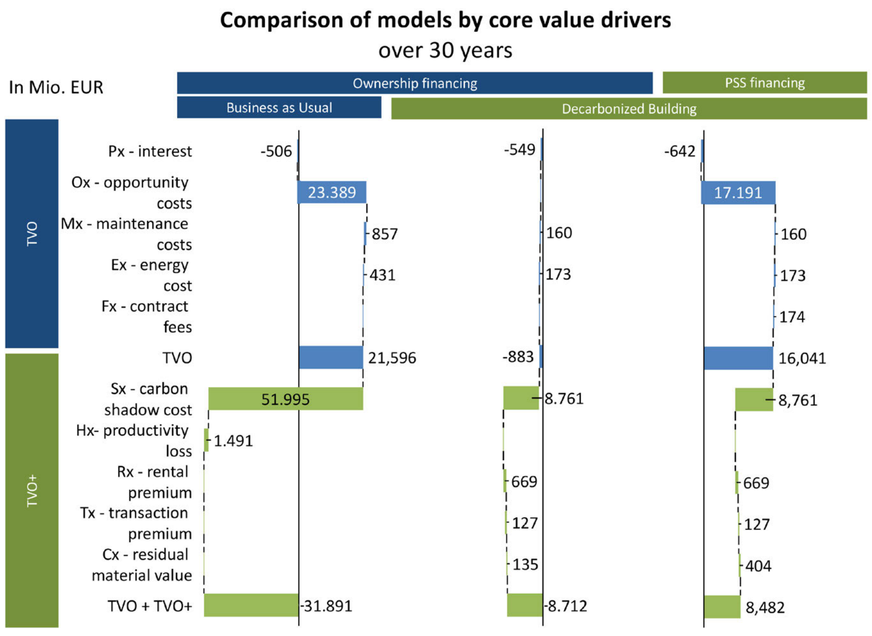

FIG. 6.3 Total Value of Ownership comparison (in €/m2) between three strategic scenarios for a potential deep commercial building energy renovation project over 30 years. The results of the 30-year cashflow are also summarised in terms of the NPV of each investment scenario.

6.4 Sensitivity analysis

6.4.3.1 Dynamic Monte Carlo simulation using SimVoi add-in

For the sensitivity analysis through Monte Carlo simulation using SimVoi add-in for Microsoft Excel we select the parameters most determinant to results of the static archetypal Dutch case-study building: Shadow Carbon Cost indexation (in years 1–10) and Weighted Average Cost of Capital (WACC) to determine Opportunity Costs. In addition to WACC, we also test the servicing cost of the loan as part of the Initial Investment to explore results from the point of view of different types of investors (private, corporate, public), for which this specific parameter can vary significantly.

Variable 1: Shadow Carbon Cost indexation is tested in two ranges: (1) A high indexation in the range of 2–100% over the first 10 years, which reflects the real externality costs which the IPCC has established as necessary to achieve climate-change mitigation goals (de Coninck et al., 2018); and (2) A low indexation range of 2– 10% over the first ten years, which might be politically realistic but most likely insufficient to achieve sufficient systemic change.

Variable 2: Opportunity Cost and Initial Investment are tested in a range of values provided for WACC and servicing cost of the loan through an asset-backed loan index. WACC ranges between 2.5% (low-risk public funding) and 10.1% (high-risk private equity funding), with the most likely mean being the 6.3% average value used in the static simulation. The servicing costs are tested as an asset-backed loan index ranging between 1.5% (representing an owner-occupied property) and 4.5% (high-cost rental mortgage) (DomiVest 2020).

Table 6.5 shows the results of the Monte Carlo simulation after 1000 simulations based on random triangular distribution function.

TABLE 6.5 Results of the dynamic Monte Carlo simulation.

	NPV after 1000 simulations				
Variable 1	BaU	OWN	PSS	NPV	Variable 2
High shadow costs indexation (2% to 100%/year over first ten years)	€ 6.970,00	€ 49,00	€ 6.045,00	Max	
	€ 4.773,00	€ 10,00	€ 4.790,00	Mean	
	€ 982,00	-€ 122,00	€ 2.679,00	Min	
Low shadow costs indexation (2% to 10%/year over first ten years)	€ 6.970,00	€ 49,00	€ 6.045,00	Max	
	€ 2.743,00	€ 291,00	€ 4.444,00	Mean	
	-€ 30.887,00	-€ 5.492,00	€ 2.679,00	Min	

The colour gradient highlights investment performance, with dark green representing the better-performing cases, yellow representing intermediate results, and dark red representing the worst-performing cases.

The results of the dynamic study show that the highest NPV (6.970 EUR/m^2) is found with the BAU (no intervention) scenario when Shadow Carbon Cost Indexation is 2.0%, WACC is 10.1% and loan interest rate is 1.5%. The same parameters also result in the highest NPV the PSS model can achieve, 6.045 EUR/m^2. In the case of the Ownership-based scenario the same best-case parameters result in a relatively small positive performance (49 EUR/m^2), as added values largely fail to compensate for opportunity costs. The worst performance for all scenarios occurs when Shadow Carbon Costs Indexation over the first ten years is at its highest (10% or 100% per year), and loan interest rate is at its highest (4.5%). The BAU scenario will then have its worst performance (−30.887 EUR/m^2) when the WACC is highest (hence highest opportunity losses). The Ownership and PSS scenarios will have their worst performance when the WACC is at its lowest (2.5%) resulting in NPV's of −5.492 EUR/m^2 and 2.679 EUR/m^2, respectively.

6.5 Conclusions

The static (archetypal Dutch case-study building) and dynamic (Monte Carlo simulation) provide clear evidence that Product-Service System (PSS) financing of a deep building energy retrofit can act as a future-proofing alternative for building owners and investors. It allows them to still benefit from the opportunity value of alternative investments by unlocking (part of) the initial capital – or credit – available to them. It also allows owners to benefit from hard and soft added values such as a premium on rental income and transactional value due to better energy and indoor comfort performance. Meanwhile, it limits the investment decision's sensitivity to potential losses caused by decreased user productivity (e.g. due to poor indoor comfort) or by an increase in shadow costs (e.g. from higher carbon taxation resulting from governance changes).

The Monte Carlo simulation shows that, under most conditions and when accounting for at least present-level carbon taxation, the PSS retrofit can be the safest strategic option. Under specific conditions (i.e. very low carbon tax indexation and opportunity value possibilities), Business-as-Usual (BaU; no intervention) performs best, but PSS still provides the best Mean and Minimum performance results, while achieving Maximum (best-case) results within a reasonable range of the BaU scenario.

The results would point to a PSS retrofitting alternative being a promising strategy to:

- **Overcome decision threshold barriers:** For example, from investors who are not considering a deep energy retrofit due to the opportunity cost of using their potential leveraged capital for a more attractive or more core-business-related investment;

- **Decrease sensitivity to market conditions:** By limiting the range of financial performance of the retrofit investment, particularly on the Minimum (worst-case) end, while providing future-proofing to uncertain changes in policy such as carbon taxation.

The ownership-based retrofit scenario shows a mostly neutral performance, meaning the value created by the retrofit is in most cases offset by its capital costs and foregone opportunity value. This represents a risk to the average investor in case the added values (e.g. rental income and transactional value) fail to materialise due to worse-than-expected market conditions. Again, this explains the empirical evidence of real estate market across Europe, and the constant failure to meet deep energy retrofitting quotas through traditional decision-making and project finance means.

6.6 Policy recommendations and research limitations

In view of the results, the authors recommend developing standardised valuation models which account for energy and carbon savings, circular use of resources, increased rental income potential and property value, and other hard and soft costs and values. This to enable *monetisation of co-benefits* (or co-liabilities) that would incentivise capital flow towards performance-based building energy retrofit solutions (den Heijer, 2013). This paper proposed a Total Value of Ownership (TVO) methodology for accounting for a specific set of values during the investment analysis process. While regional average figures were used, the authors acknowledge that in the case of both hard and soft values and costs, the actual figures used in an investment analysis are deeply specific to each type of building owner down to the individual organisation.

Figure 6.4 presents a first approach, and non-exhaustive list of hard and soft values and costs which the authors believe should be standardised and considered when making building (retrofit) investment decisions, and which should therefore be the focus of further study.

Only the individual characteristics and goals of an organisation can determine the value that different benefits and co-benefits have in the process of pursuing these goals. For example, corporate and public real estate owners are less likely to benefit from the potential rental income increase resultant from a better-performing building, as these organisations tend to be owner-occupiers of their buildings. Increase in property value, however, can still be considered as a hard benefit, since the building can be used as collateral for other investment projects the organisation might want to undertake in the future. The benefit of the approach presented in this paper is to account for: a. opportunity cost (and value) of alternative financing models, and b. monetised softer values which are usually considered only as abstract (but financially irrelevant or uncertain) co-benefits. The use of a statistical model based on Dutch national average figures – rather than a (set of) specific case-study building(s) – aims to account for the individual characteristics of each building owner and their specific value assessments. Any size of case-study building dataset would still represent only a limited sample with non-replicable results.

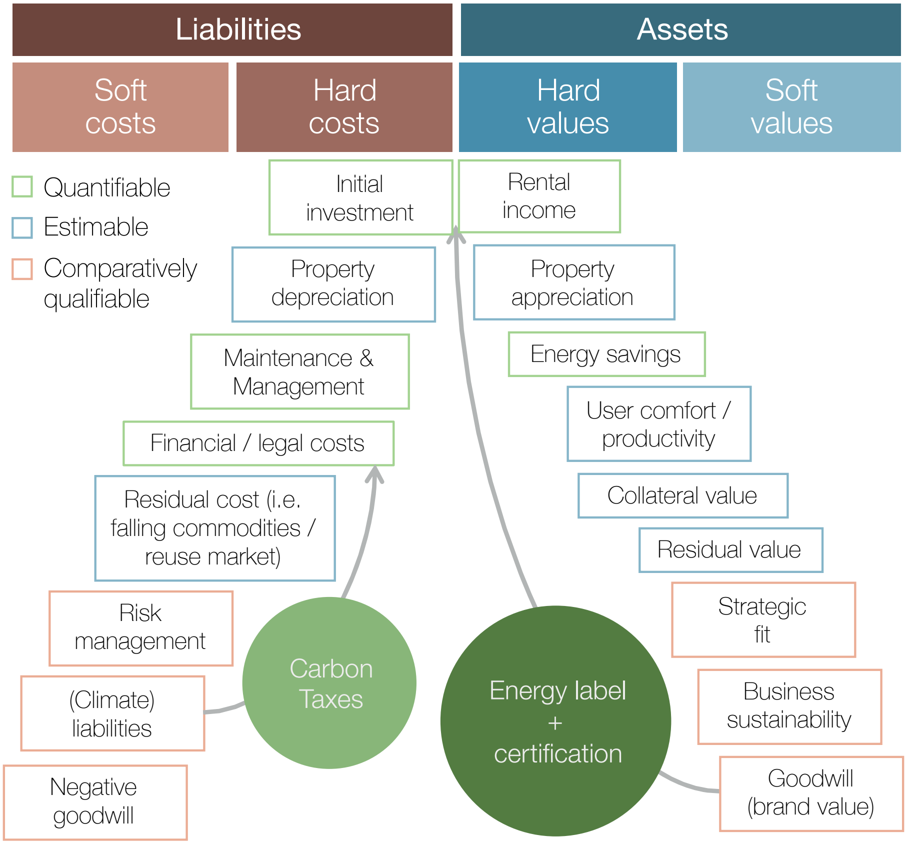

FIG. 6.4 Non-exhaustive diagram of soft and hard values and costs which the authors recommend should be further studied and standardised. Policy instruments such as energy labelling and carbon taxation, and market instruments such as commercial certification standards are shown as examples of methods for the negative (cost) and positive (value) monetisation of soft parameters.

To overcome the barrier of higher Net Present Value (NPV) for no intervention scenarios, policy could help by demanding periodic technical reporting from owners of currently financed (e.g. mortgaged buildings) and penalising them for deferred maintenance, on the grounds that it will result in loss of value or higher future reinvestment requirements.

Lowering capital costs for projects that meet a certain de-carbonisation performance or material circularity objective is another powerful tool available to decision-makers in public policy, as well as to investors such as banks, to increase demand for such interventions.

In the case of soft costs such as user comfort and performance, which are the subject of scientific debate, the authors propose that building owners use an inverse approach: Namely, to calculate at which cost of personnel productivity drop or shadow carbon taxation does the decision not-to-renovate become untenable. Such risks can then be considered when making long-term strategic decisions.

Because commercial parties generally have a high Weighted Average Cost of Capital (WACC), the costs of externalising energy retrofits trough PSS might not be drastically different compared to financing the entire project themselves. In the case of this type of owner, whether public or corporate, the attractiveness of PSS models lies in ease of processes in the achievement of soft social and environmental values related to their real estate portfolio. The methodology applied in this paper can be adapted for use in residential buildings. In this case the authors have decided not to do so since residential buildings are both technically (i.e. solid walls rather than curtain walls) and administratively (i.e. decentralised rather than centralised financing and decision-making) different from commercial ones, and the two sets of results would render the outcomes of this study too complex and confusing.

Finally, to upscale a PSS financing model for building retrofits and through it enable the transition to a circular economy, it is crucial to (1) develop standardised contracting and financing models to lower setup and management costs and (2) develop a track record of implemented PSS models. This will support their bankability and insurability, i.e. lower interest rates and financial premiums to cover risk and uncertainty. Previous work (Azcárate-Aguerre et al., 2018) has highlighted that it is unlikely for façade suppliers to be able to pre-finance Facades-as-a-Service (a sub-type of PSS) offerings. This restriction sets service providing parties in the construction industry apart from the great PSS transition success cases of other sectors (Joris Van Ostaeyen, 2014) and illustrates the need to create well-founded financial cases for third-party investors and other financial institutions.

Regulatory measures, corporate responsibility initiatives and emerging societal trends can support each other. This can allow for rapid change as demonstrated – for instance – by the successful Energy Labelling of Buildings (EU Directive 2002/91/EC) system being replicated in many parts of the world.

Chapter Conclusions

The chapter concludes that the investment decision-making process behind building envelope construction and renovation is skewed towards linear construction models. This is the result of an insufficiently complex and fair evaluation process, which would consider and internalise indirect and intangible monetary costs and values to the client organisation, the supply-chain, and society as a whole.

Even while focusing only on the investor's perspective, a focus on minimising initial direct project costs can result in significant opportunity costs in the form of increased maintenance expenses, unachieved energy savings, and missed property value gains (both as collateral and as an exploitable profit-generating object). If one looks beyond the investor, systemic failures such as loss of material resources, pollution, excessive energy use, and unachieved user comfort and health performance are just some of the recognisable opportunity costs of sub-optimal investment decisions resulting from insufficient and oversimplified financial evaluation models.

Valuators, investors, and financiers must jointly develop much more complex and fair evaluation models, which internalise the opportunity costs and values mentioned above, and while doing so balance the playing field for more holistic and sustainable investment decisions to be made.

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7 The management dimension

The impact of performance-based contracts for building energy renovations on real estate development and procurement models and management processes

The chapter has been published as "Azcárate Aguerre, J. F., Den Heijer, A. C., Arkesteijn, M. H., Vergara, D. A., & Klein, T. (2023). *Facades-as-a-Service: Systemic managerial, financial, and governance innovation to enable a circular economy for buildings. Lessons learnt from a full-scale pilot project in the Netherlands.* Frontiers in Built Environment, 9, 55."

ABSTRACT

Introduction: The challenge of the energy transition in the built environment has, in recent years, been exacerbated by rising awareness of the material resource limitations we face on the path towards sustainable development. In this context the concepts of Circular Economy (CE) and Product-Service Systems (PSS) have emerged as potentially complementary industrial and business strategies to overcome the interdependent material resource and clean energy challenges. **Research significance:** Research in the field of circular and PSS-based construction frequently centres on the design and engineering of products, mainly through technical strategies such as design for disassembly and adaptability, and the use of the different "R's" (Reuse, Repair, Re-manufacturing, etc.) to extend and/or reset the service lives of building materials and components. Such an approach often ignores the fact that these strategies require changes in the management, financing, and governance aspects of products and therefore buildings, throughout their entire

service-lives. This paper will focus on the systemic administrative (i.e. management, financing, and governance) challenges of the circular and servitisation transitions in the building and construction sector, to enable products which are "Circular by Design", to effectively support regenerative processes.
Research question: The paper asks how traditional building products' management, financing, and governance processes prevent or delay the implementation of CE and PSS models. It explores the demand side's perspective (commissioners, building owners and facility managers), taking a systemic view to the search for new practical, strategic, and scalable administrative models.
Methodology: The research method applies the DAS model (De Jonge, Arkesteijn et al. 2009, Van der Zwart, Arkesteijn et al. 2009, den Heijer 2011, den Heijer, Arkesteijn et al. 2016) to data gathered from focus group discussion and co-design sessions involving multidisciplinary teams of experts from both academy and industry, as well as literature. The research was conducted within the context of the TU Delft CiTG Facades-as-a-Service full-scale pilot project.
Results: The research has shown that, while PSS models to enable material circularity can be partially implemented within the current managerial, financial, and governance framework, this implementation is not efficient, effective, or scalable. This is because standard modes of operation in these disciplines are misaligned with that goal. The practical barriers resulting from this misalignment increase the complexity, risk perception, and therefore cost of PSS alternatives, and thus prevent their organic adoption despite increasing market interest. Recommendations are made for policymakers, financiers, suppliers, and building owners to overcome these barriers.

Chapter summary

The strategic priorities, operational needs and commercial interests of demand-side stakeholders such as real estate developers and operators, facility managers, and investors, will ultimately determine the success or failure of a PSS approach to façade procurement. The higher intrinsic cost of externally financed contracting models, such as lease or Pay-per-use, means that non-financial considerations must deliver enough added value to a potential customer to outweigh the higher direct financial costs. The extent to which FaaS models can support the long-term strategic goals of real estate operators will determine the attractiveness of this value proposition.

This chapter explores the possible impact of Product-Service systems when applied on a broad real estate portfolio management strategy, and beyond the building envelope alone. In the most extreme scenario, it is envisioned that buildings could become a collection of ongoing service contracts, each one fulfilling a specific building system demarcation and spanning widely diverse time-scales according to the expected service-life and replacement rate of components.

Benefits for real estate operators could include: Flexibility of portfolio to changes in user and technical requirements, implementation of CE principles through extended producer responsibilities, and streamlining of in-house operations leading to leaning of the organisation's processes and payroll.

Drawbacks of such an extreme approach could include: Loss of portfolio value as capitalisation leverage, complexity of contract enforcement operations, and risk of external ownership of systems which are key to the organisation's core business.

The study presented in this chapter builds upon the "Designing an Accommodation Strategy" (DAS model) (Arkesteijn, Valks, Binnekamp, Barendse, & De Jonge, 2015) to evaluate the conditions under which such a cost-benefit analysis would be in the interest of a target organisation. Differences between market sectors are highlighted and a possible long-term roadmap for the servitisation path is proposed.

7.1 Introduction

The need for radical systemic change to render the global built environment more resilient and sustainable has been amply recognized for decades. The clean energy transition, rooted in the energy crisis of the early 1970's, has seen a slow and ineffective uptake: the majority of buildings, even in developed countries, still have an energy performance significantly below the desired standard (BPIE, 2019). At the same time, the rate of renovation is consistently below that required to meet climate change mitigation goals established by the Paris Agreement and 2050 climate neutrality targets set by the EC. At the current rate of 1% it will take around 100 years to renovate the European building stock (Artola, Rademaekers et al. 2016, European Commission 2016, Magrini, Lentini et al. 2020).

This disappointing performance is not the result of technological insufficiency. (Near) Zero-Energy Buildings (NZEBs) use a variety of complex technological components and systems to reduce operational energy consumption, while being able to generate enough renewably-sourced energy to offset the remaining need. Rather, it is the result of administrative barriers such as complex decision-making processes, split incentives, lack of access to finance, lack of leadership, and short-terminist thinking (BPIE 2011, The Economist Intelligence Unit 2013). The construction and real estate market is, in other words, failing to assign a fair value to climate-change mitigation strategies, or to fairly appraise the risks of non-mitigation.

In addition to the clean energy transition challenge, a new awareness has been growing over the last decades of the interrelated issue of the availability of raw materials needed to deliver and run NZEBs. NZEBs rely not only on the traditional building materials associated with the construction industry (steel, concrete, brick, wood, etc.), but increasingly demand high-value and critical materials such as those found in electric engines, electronic circuits, and renewable power generation and distribution technologies (BIO Intelligence Service 2013, Fox-Penner 2014, Abraham 2015) to meet ever more demanding requirements in terms of energy and environmental performance, health, safety, and comfort. Many of these material elements hadn't been part of the built environment until a few decades ago.

For reasons ranging from dwindling volume of global deposits to increasing difficulty and cost of extraction, or geo-political and financial limitations, access to ever more crucial raw materials is under constant and growing pressure. Rising mainstream awareness of this raw material challenge has recently been exacerbated by noticeable supply-chain crises fuelled by the COVID-19 pandemic and the geopolitical Russo-Ukrainian conflict (World Economic Forum 2022).

In this context the Circular Economy (CE) has in recent years gained a prominent role in both academic and professional discussions on sustainable and regenerative development. In the construction sector, CE theory aims to address the material challenge presented by the need to meet demands for increasing housing and infrastructure pressure fuelled by a growing global urban population, by the urgent need to renovate the existing building stock, and by rising living standards across the developed and developing worlds, with the imperative of ensuring access to resources for future generations (Behrens, Giljum et al. 2007, Krausmann, Lauk et al. 2018).

Product-Service Systems (PSS) have gained increasing traction (Camilleri 2019) as a potential instrument to enable the Circular Economy transition. This since the redistribution of incentives, responsibilities, and risks proposed by PSS models could support addressing the administrative systemic challenges previously mentioned. PSS is a range of business and industrial models which aim to refocus companies' value proposition from delivering tangible material products towards guaranteeing agreed performance requirements over a defined period of time (Tukker and Tischner 2006, Stahel 2010). If the performance requirements include environmental and CE indicators, PSS allow decoupling value-creation from resource consumption while promoting regenerative industrial practices (Fischer, Steger et al. 2012, Vezzoli, Kohtala et al. 2017). By doing so PSS creates a financial incentive for more diligent material stewardship (Widmer, Tjahjono et al. 2018).

Several research projects have explored the development of PSS for application in the built environment. While frequently initiated from a technology / product manufacturer perspective (i.e. supply push), such initiatives frequently expose the interdisciplinary and cross-stakeholder nature of PSS and CE thinking. A limitation of the studies so far is their theoretical nature. Our research goes beyond what has been done until now by engaging a large consortium around a real full-scale pilot testbed, the "Façades-as-a-Service" (FaaS, a.k.a. Façade Leasing) project. The project has involved building system suppliers, façade fabricator, facility managers, financiers, and real estate developer/operators, supported by multi-disciplinary experts from academy. The aim of FaaS is to test the real life implementation of a PSS for the deep energy renovation of a 3000m^2 high-end façade of the Civil Engineering and Geo-Sciences (commonly referred to as CiTG after its Dutch acronym) building at TU Delft campus, in the city of Delft, The Netherlands.

7.2 Research question & Hypothesis

This paper is the result of a one-decade-long and ongoing research on the implementation path for CE-enabling PSS through the FaaS project, coordinated by TU Delft. The research question behind this paper is to understand how traditional building management, financing, and governance prevent or delay the implementation of CE-enabling PSS models for whole buildings or whole parts of buildings, using the renovation of a high-performance building as a testbed. The hypothesis was that a) current administrative processes (Business as Usual i.e. 'BAU') would hinder PSS by failing to assign a fair value to climate-change mitigation strategies, or to appraise the risks of non-mitigation. And that b) a high degree of process customisation would allow the implementation of CE-enabling PSS for the façade in question, but result in a slower, more expensive, and potentially riskier project than its 'BAU' alternative.

7.3 Materials & Methods

Focus-group discussions within previous stages of the FaaS project (Azcárate-Aguerre, Klein et al. 2018) led us to identify the key traditional administrative processes and objectively determinant factors to the success of a FaaS procurement model, that need to be addressed to answer our research question and prove our hypothesis, shown below in Table 7.1.

TABLE 7.1 List of factors determinant to the success of a FaaS procurement model.

Administrative process	Factor determinant to the success of a FaaS procurement model[1]
Strategic management	Value hierarchy
	Commissioners' organisational structure
	Project briefing
	Contractual structure (the SPV model)
	Material circularity
Project finance	Financial evaluation of the project
	Transfer tax and Value Added Tax
	Bankability: Impact on underlying cost of capital
	Material markets: The problem of guaranteeing residual value
	Financial evaluation of the project
Governance and building law	Legal framework for value preservation and the argument for concentrated ownership in the real estate sector
	Physical demarcation of materials, components, and systems
	Technical demarcation of performance, responsibilities, and risk
	Risk distribution and bankruptcy law

The DAS (Designing an Accommodation Strategy) process model (De Jonge, Arkesteijn et al. 2009, Van der Zwart, Arkesteijn et al. 2009, den Heijer 2011, den Heijer,

1 The technological dimension is partially beyond the scope of this paper, and has been described in closer detail in Azcárate-Aguerre, J. F., T. Klein, T. Konstantinou and M. Veerman (2022). "Facades-as-a-Service: The Role of Technology in the Circular Servitisation of the Building Envelope." Applied Sciences **12**(3): 1267.. In the present study technical requirements are discussed as a boundary condition to the decision-making process of other stakeholder disciplines. In a similar manner, financial project evaluation has been expanded upon in a separate publication Azcárate-Aguerre, J. F., M. Conci, M. Zils, P. Hopkinson and T. Klein (2022). "Building energy retrofit-as-a-service: a Total Value of Ownership assessment methodology to support whole life-cycle building circularity and decarbonisation." Construction Management and Economics: 1-14.. The present paper focuses on the systemic and strategic interaction between different disciplines, and the current real-world constraints which prevent the organic adoption of PSS contracting models in the built environment.

Arkesteijn et al. 2016) was applied to the three categories management, finance, and governance to extrapolate actionable lessons from the collaborative strategic learning process of implementing PSS through a cross-sectoral and multi-stakeholder systemic innovation approach. Figure 7.1 shows the structure of the DAS method:

- **Task 1**. Assess the current portfolio: Determine current (mis)match in process and product.
- **Task 2.** Explore changing demand: Determine changing strategic and functional, organisational, and societal requirements.
- **Task 3**. Generate future models: Weigh and select alternatives.
- **Task 4.** Define projects to transform: Detailed attainment plan.

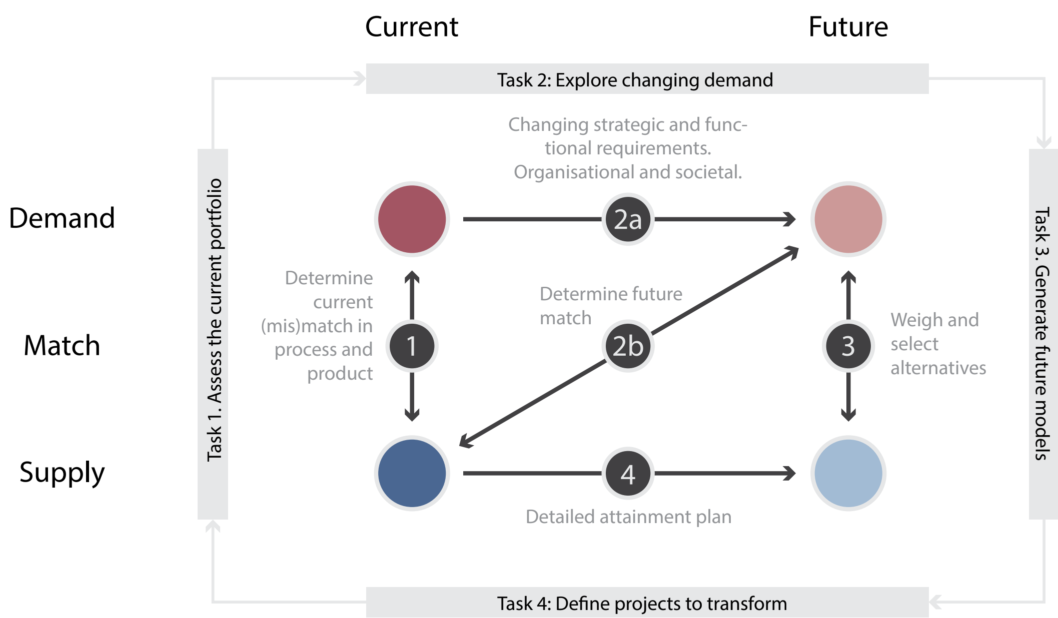

FIG. 7.1 Designing an Accommodation Strategy (DAS) in five steps. (Adapted from De Jonge et al., 2009, p. 36; den Heijer, 2011, p. XV)

For this paper, Task 1, Task 2, and Task 3 were used as a basis to structure the collection, analysis and evaluation of the data, while Task 4 is the basis to present and discuss the results and generate recommendations for future developments.

Data for the analysis was collected through empirical evidence gathered from the Facades-as-a-Service (FaaS) project combined with secondary sources. Sources of data include a detailed diary summarising the discussions and outcomes of dozens of co-development meetings between academic and professional experts from different disciplines related to the fields identified above, a record of email threads with attachments, as well as commented legal contracts and other documents related to the most critical discussion points. Lastly, it includes three final reports per year of the project summarising the systemic business model development, the technical execution process, and societal and market dissemination activities (Azcárate-Aguerre, Klein et al. 2020, Azcárate-Aguerre, Klein et al. 2020, Azcárate-Aguerre, Klein et al. 2020). Also in the context of this project a state-of-the-art review was performed on recent and ongoing circular business model research and pilot projects (Vergara d'Alençon, Arkesteijn et al. 2019).

7.3.1 The CiTG Pilot Project at TU Delft (Tasks 1 to 3)

7.3.1.1 Task 1: Assess current portfolio Determine current (mis)match in process and product

As presented in the Introduction, there is a mismatch between the fact that the product: the building sector, is not contributing enough to the process: climate neutrality and long-term sustainability (resilience) set by and for society. As mentioned, this is evidenced by slow energy renovation rates, leading to high carbon emissions, and no concern for circularity, further increasing emissions and other negative externalities such as pollution, as well as putting at risk the availability of crucial materials and resources for future generations.

The CiTG building selected for the FaaS project exemplifies this mismatch and is thus an appropriate testbed for our analysis. This representative building, constructed during the mid-1960's, displayed many of the performance issues and decision-making challenges common to buildings of that time: its envelope consisted of a painted, uninsulated steel frame with single glazing, and no active ventilation was present in the building. Passive ventilation through manually operable windows in each office space was further hindered when the originally open stairwells had to be enclosed in order to meet new fire-safety standards, thus reducing cross-ventilation and preventing a cooling stack effect through the building. Lastly, an internal and manually operated blind system provided limited prevention to over-heating of the office spaces in the summer, by allowing most of the solar radiation in through the single-glazed façade. As a result, the building consumed large amounts of non-renewably supplied energy and thus did not contribute to climate neutrality goals.

In 2018 the West façade of the building was the target of a minimal maintenance effort which mostly consisted in the repainting of façade frames to prevent their further corrosion and the resulting technical and visual deterioration. This work did not contribute to improving the energy or comfort performance of the building envelope. The main reason provided by decision-makers for the choice of maintenance plan was 'short available strategic planning horizon', because relevant stakeholders were debating whether the building would be generally decommissioned and replaced within a 10–15-year period. This represents a violation of the principles of CE, which include applying a hierarchy of "reduce, reuse, re-manufacture" to products. The imperative of reducing the use of new raw construction materials, in this case, would have dictated reusing the CiTG building to the fullest extent possible, rather than demolishing it.

7.3.1.2 Task 2: Explore changing demand: Determine changing strategic and functional, organisational, and societal requirements

In 2019, when the same minimal maintenance work was being planned for the East façade of the building, a consortium of academic and professional experts came together to explore the possibilities of procuring a new façade instead, commissioned through a performance-based contract. Following from research by Den Heijer (den Heijer 2011, den Heijer 2013), the research aimed to include the perspectives of as many relevant stakeholders as possible. In particular, the key decision-makers behind the four main value criteria: Strategic management (represented by TUD board of directors and TUD Campus Real Estate (CRE's)'s project development team), Project finance (represented by TUD central corporate finance and TUD CRE's financial department), Technical (represented by a Façade supplier consortium and TUD CRE's project development and facility management teams), and Sustainability performance (represented by Academic advisors and TUD CRE's energy team).

The key performance indicators according to the perspectives of these four target stakeholder groups were summarized into a series of functional and strategic requirements, tangible and intangible, described in Table 7.2.

TABLE 7.2 List of functional and strategic requirements for the performance-based renovation of the CiTG East façade.

Requirements	Baseline value (Current scenario after minimum maintenance)	Target value (Future desired scenario)
Technical readiness		
Energy use (kWh/m^2/year)	214,3	< 50
User comfort (Over Kelvin hours/year (DIN4108))	> 300	< 10
Shading system (internal/external, wind-resistance)	Internal blinds	External blinds
Ventilation (manual/automated)	Manual windows	Manual windows + automated night-cooling
Ventilation (passive/active)	Passive	Passive
Technical and user-comfort monitoring	None	Technical + user comfort monitoring
Façade circularity potential	Low-level recycling or landfilling (due to present asbestos)	Full reuse/re-manufacturing potential
Strategic management		
Commissioning team structure	Linear (stage)-based	Integrated across all service-life steps
Budget allocation to projects stages	Fragmented budget from diverse departments (development, facility management, end-user, et.)	Integrated budget
Maintenance responsibility costs over following 15-30-year period.	Internal (TUD Delft Campus Real Estate)	External (FaaS Provider)
Project finance		
Total Cost of Ownership (compared to baseline)	100%	<120%
Financing	Internal (applied for and served by building owner)	External (applied for and served by FaaS provider)
Cost of capital	-0,5%/year	<1,5%/year
Value of building as collateral	100%	100%
Residual value	Depreciation to zero.	Depreciation to 10% of the original cost (indexed to account for inflation).
Governance and building law		
Toxic material liability (Asbestos present in existing façade)	Liability of owner.	Liability of FaaS provider.
Recovery of material value from existing façade	Asset/Liability of owner.	Asset/Liability of FaaS provider.
Material recovery (new façade)	Asset/Liability of owner.	Asset/Liability of FaaS provider.

The authors of the paper acknowledge that the requirements list is missing critical parameters related to carbon performance. This omission of embodied carbon requirements is due to the lack of broadly recognised methodologies for calculating the embodied carbon of circular technical solutions. Operational carbon requirements are also excluded since they are they are determined by the building's and the TU Delft campus' central energy systems, which are beyond the scope of the CITG's East façade renovation project.

7.3.1.3 Task 3: Generating future models: Weigh and select alternatives

In this phase, the multi-stakeholder consortia led by TU Delft co-designed a feasible decision-making route to decide between a standard and a PSS procurement and contracting models. The decision would have to flow based on the evaluation of each model's costs and uncertainties linked to meeting the requested requirements. Participating organisations from various fields contributed data on practical experience and expertise for the evaluation of the 'standard' procurement and contracting model, while previous phases of the Facades-as-a-Service project contributed data for the evaluation of the PSS model, albeit on a theoretical basis (Azcárate-Aguerre, Klein et al. 2018). These sets of data were used as a basis to design a decision-making process and time-line, structured on the achievement of gradual and specific milestones, from the diverse discipline perspectives, summarized in Figure 7.2.

As a result, TU Delft's Campus Real Estate presented the University's Board of Directors, the final decision-maker, with information comparing three scenarios:

- **Business as Usual (BAU):** A minimum renovation work on the existing East façade, modelled on the works on the West façade procured through a traditional 'linear' purchasing model.

- **Traditional baseline renovation:** Replacement of the East façade through a traditional 'linear' purchasing model. Some product innovation would be implemented, beyond the technical requirements traditionally established in the procurement process, but no systemic contractual innovation would be implemented.

- **Extended FaaS requirements:** Replacement of the East façade through a systemically innovative 'circular' PSS model. Technical and organisational innovation would be implemented, beyond the technical requirements traditionally established in the procurement process.

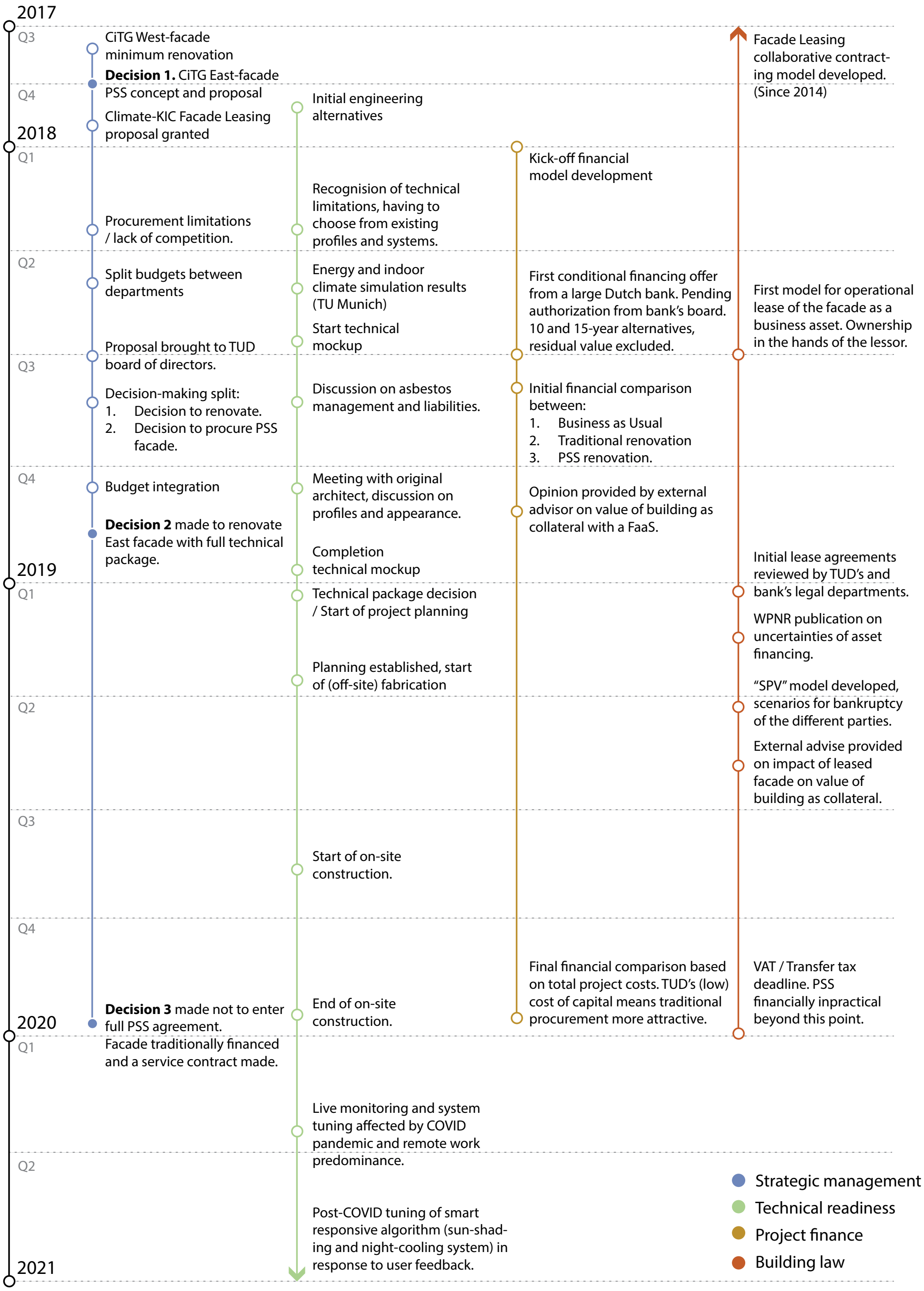

FIG. 7.2 Timeline for the CiTG East façade renovation decision-process, and the several multi-disciplinary discussions and milestones contributing to these decisions.

Due to their relatively old and/or heritage building portfolios, retrofit decisions are a challenge common to TUD and other universities. At the time (2020) TUD had to make decisions on the renovation of three of its largest buildings, and resources allocated to these projects in that year's budget was only sufficient for one of them. This illustrates the types of constraints faced even by building owners with relatively extensive resources. Below, we summarize the decision-making process for each scenario.

Decision 1: Business as Usual

TUD's Board of Directors recognised the long-term sub-optimal nature of this comparatively inexpensive and fast but under-performing solution. However, on the one hand, a minimum scheduled maintenance could not be put on hold indefinitely while other options were weighted, because corrosion would start affecting the window frames to an irreversible extent. On the other hand, since no energy performance or user comfort improvement was expected from a minimal intervention, there was no pressure from the end-user (the CiTG faculty) to schedule these measures sooner. In fact, the end-user welcomed the opportunity to consider a more extensive renovation project which would contribute to better energy and user comfort performance. If the façade wasn't improved at the time, another 6 to 10 years would pass before the BAU maintenance had depreciated down to zero, and a decision could once again be considered.

The decision was taken early in the process, In Q4.2017 and even before the project grant had been awarded, to temporarily suspend the planned minimum renovation project on the East façade of the CiTG building.

Decision 2: Traditional baseline renovation

A full decision for a FaaS renovation couldn't yet be taken, as it required further research, but once the BAU scenario was placed on hold, a decision would have to be made on whether the CiTG's East façade would be renovated by Q4.2019, or the BaU scenario would be reinstated to prevent damage to the façade.

The choice was then made to split the decision in two: In Q3.2019 green light was given to the technical CiTG East façade renovation project, so that planning and fabrication could start, and the façade could be replaced between late Q2.2020 and Q4.2020. The decision whether to implement the FaaS model would be delayed until further research was carried out in early 2020.

Decision 3: Extended FaaS model implementation

Once technical decisions had been made and the construction execution process had started, the focus of the project team and the multiple academic and professional advisors could shift towards Task 4, addressing the broader systemic challenges to the FaaS model implementation. Lessons learnt are summarized and presented in the Results section.

Several constraints resulted difficult to overcome, and the final decision was not to enter a full PSS-based FaaS contracting and financing model covering all requirements from Table 7.2. This as the building owner and not the façade provider is the owner of the façade. Still, a service contract was developed and entered between the building owner and the façade provider. An innovative aspect of this contract is that it is based on the ongoing provision of the Technical and Strategic performance requirements specified in Table 7.2.

7.4 Results

7.4.1 Task 4: Define projects to transform: Detailed attainment plan

In this phase, the consortium set up and defined the proposed FaaS model in terms of its technical, managerial, financial/fiscal, and legal implications. During the co-development process the project consortium aimed to limit as much as possible the number of diverse systemic innovations required for the FaaS model to work. In other words, it attempted to fit performance-based procurement ambitions – to the largest extent possible – within the traditional processes of the real estate and construction sectors. The process and findings from each disciplinary perspective are summarised in the Results section below.

The results of the study (Task 4) are presented below in a summarised form and organised according to the three disciplinary fields previously identified in Table 7.2. An extended version of these results is provided as additional reference to the reader, in Annex 7.6.

7.4.1.1 Strategic Management

The life-cycle of a building project – from its initial conceptualisation through its commissioning, operation, and final decommissioning – is guided by traditional and well-established processes which aim to minimise uncertainty and risk. These traditional processes result in systemic inertia across the built environment, resulting in the slow rate of change commonly associated with the construction sector. Decisions are constrained to a narrow range due to prescriptive financial evaluation models, organisational structures, and contracting mechanisms.

From the initial planning of a new construction or renovation project, financial feasibility models tend to focus on a specific range of values and liabilities. These as determined by the type and priorities of commissioning organisation, see Figure 7.3. A narrow focus on short-term hard costs and values lead to a wide range of project choices being discarded from an early phase. The lack of standardised and comprehensive Total Value of Ownership models, which include not only short-term, hard values and costs, but also long-term, softer parameters and externalities, distorts the decision-making process in the benefit of well-known and well-tested choices.

Commissioning organisations are likewise organised according to traditional and linear practices. Building projects are frequently transferred from short-term parties responsible for developing and building the project, to long-term parties responsible for operating it. Even in instances when one single organisation is responsible for all phases, as is the case with TU Delft's Campus Real Estate, such organisations are frequently structured according to the same life-cycle stages common among independent parties, see Figure 7.4. This results in a loss of potential knowledge exchange between specialists responsible for the different life-cycle stages, loss of decision-making complexity which would benefit choices with a positive performance over the longer term, while embedding a linear mentality into the construction management process.

The procurement process traditionally focuses on specifying technical solutions, rather than establishing functional requirements. Such a prescriptive approach commoditises system suppliers competing on the basis of lowest price versus highest performance. Long-term performance is frequently beyond the producer responsibility, as is environmentally responsible or circular treatment of material resources. Client organisations (commissioners) therefore assume the risks associated with technical decision-making, component operation, building performance, user satisfaction, and final resource decommissioning and (ideally circular) material treatment.

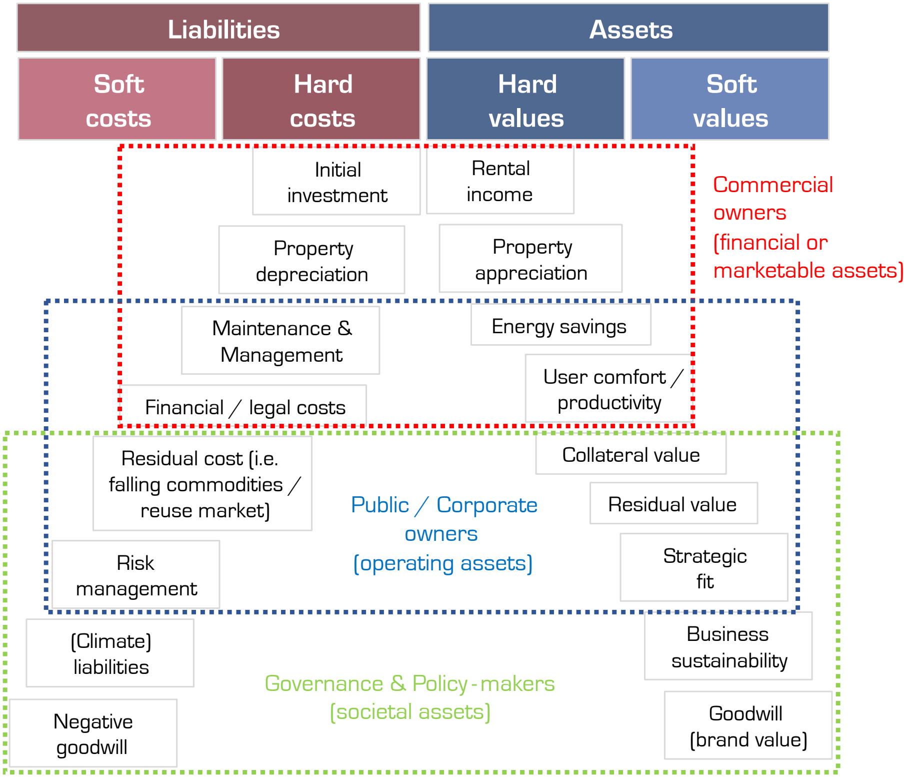

FIG. 7.3 Non-exhaustive diagram of soft and hard values and costs in strategic real estate decisions. Highlighted those parameters most relevant to each type of building owner. (Adapted from Azcárate-Aguerre, Conci et al. 2022)

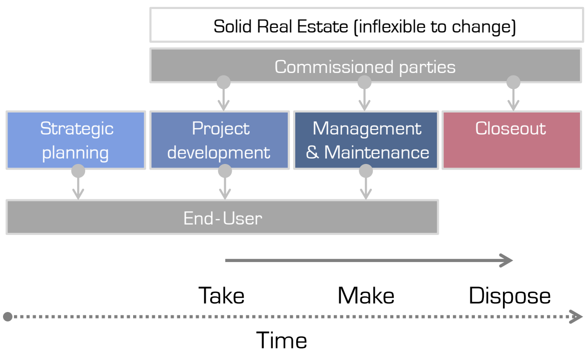

FIG. 7.4 Diagram of the "Solid Real Estate" created by development and management organisations with a traditional linear mentality.

Even if the same organisation acts as developer, owner/manager, and end-user, the stepped approach to the diverse building life-cycle stages limits strategic knowledge and priority exchange. This in turns limits the chances for innovation in the procurement and management process.

Contracting models, which are closely related to project finance and bankability, aim to minimise disputes by concentrating ownership. Alternative models for financing and managing PSS alternatives, such as the SPV model illustrated in Figure 7.5, rely on customized and untested interpretations of building, rental, and property laws. As such they are perceived, from both a legal and financial perspective, as riskier and therefore costlier. The added cost of capital from this perceived novelty and risk result in PSS models being unlikely competitors (from a cost perspective) with more traditional models of direct ownership. This hinders the up-scalability of PSS solutions, limiting them only to early adopters with strategic interests and value hierarchies beyond the directly commercial, see Figure 7.5.

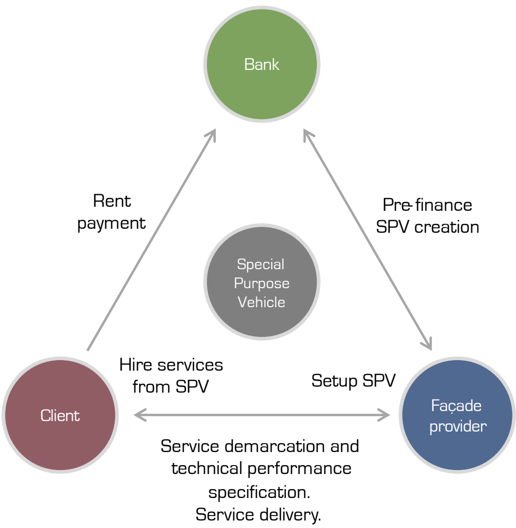

FIG. 7.5 Structure for the financing and contractual management of a Façade-as-a-Service, based on a "Special Purpose Vehicle" established by a FaaS developer and possible investor. (First published in (Azcárate-Aguerre, Klein et al. 2020).

In terms of material circularity and the regenerative decommission of building components, the study shows that effective solutions are not yet readily available for either the reprocessing of legacy equipment (reactive circularity), nor for the commissioning on new and effectively circular solutions (proactive circularity). Even commissioners willing to make the additional effort and expense of circular material treatment are most frequently unable to find a second-hand material market and reverse logistics chain capable of handling material recovery from both a technical and administrative perspective.

7.4.1.2 Project Finance

Financial performance evaluation of the project was guided by the same procedural constraints identified above and illustrated in Figure 7.3. The decision-making process was guided by hard costs and values related to capital costs, cleaning and maintenance schedules (internal or externalised in the case of PSS), financial costs and fiscal depreciation. Additional softer values such as expected energy savings and the estimated productivity value of increased user comfort were calculated as a reference, and considered in the decision-making process, but were not prioritised. Residual (circular) value of components was also excluded from the calculation, as none of the involved parties could establish a reliable methodology for assigning a financial value (or cost) to the recovery of materials at the end of the PSS façade's service life.

The results of the financial evaluation process can be found below in Figure 7.6 and Figure 7.7. From a hard value and cost perspective the Business-as-Usual alternative (i.e. not renovating the façade) was calculated to be the most financially attractive (i.e. cheapest) alternative. Only when running the calculation over a 30-year planning horizon did this change, as it would be unrealistic to expect the current façade to perform for another 30 years, so that a major renovation would be necessary. Direct purchasing of the façade would be marginally cheaper from a Total Cost of Ownership perspective over 15 or 30 years, but leasing (or PSS contracting) of the façade would result more attractive from a cash-flow perspective. These conclusions are specific to the accountancy practices of the commissioner organisation, and the way in which local fiscal regulation and project finance treat the depreciation of a building asset.

Value Added Tax (VAT) and property transfer tax have a significant impact on the PSS contracting of building components and are the object of some uncertainty due to their fiscal novelty. VAT must be paid by the FaaS owner but can be deducted since the façade is a business operating asset. The building owner, FaaS procurer, will then have to pay VAT on the ongoing monthly service fees. Transfer taxes are likely to result if the façade is transferred (to the SPV or another FaaS-owner entity) after its completion. At the time of the façade construction completion the façade would usually become legal and economic ownership of the building owner, so that its transfer to a third-party entity would result in property transfer taxes. This is unique to each country's tax code, but due to the extensive similarities between tax policies such a transfer tax is expected to result in considerable additional costs and should be considered in the project's financial and fiscal planning.

Bankability of the FaaS alternative is currently a significant challenge. The additional perceived risk of the façade being contractually disconnected from the building results in two financial uncertainties which can carry added capital costs: 1. The financing of the façade is not backed by a complete real estate asset, as would be the case in a traditional mortgage-backed loan. Since the value of the façade, as an independent asset, at any given time is difficult to estimate, the financial construction is backed largely by the solidity of the building owner as FaaS customer. This results in capital costs similar to those of a business loan, and higher than a traditional mortgage-backed loan. 2. The value of the building as collateral, for securing other mortgage-backed loans, might be negatively affected by the "lack" of a legally and economically owned façade. This was a topic of debate, since the loss in collateral value might be counterbalanced by a general increase in the property's value as a result of the new façade and its increased aesthetic, energy-, and comfort-performance.

Lastly but crucially, the difficulty of banking the residual value of materials is a crucial current hurdle to the implementation of PSS or the Circular Economy.

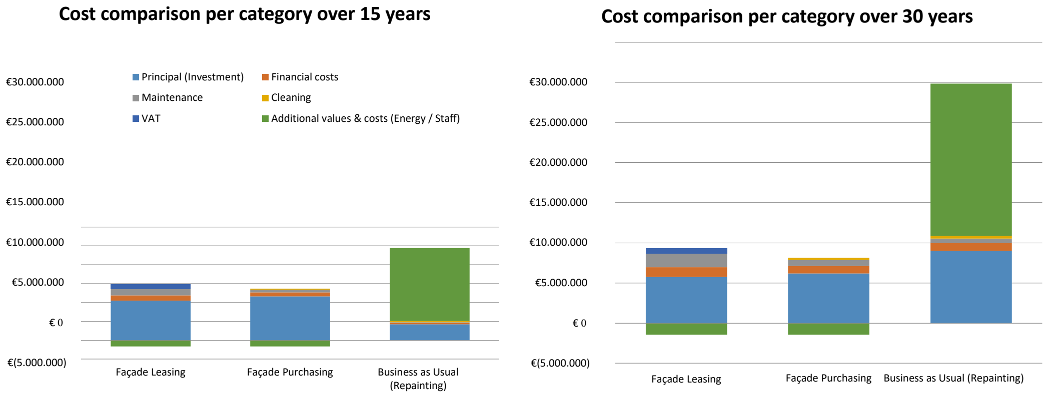

FIG. 7.6 Total Value of Ownership results comparing the three strategic scenarios for the CitG East façade renovation, including selected “soft” values, over a 15- and 30-year planning horizon. (First published in: Azcárate-Aguerre, Klein et al. 2020)

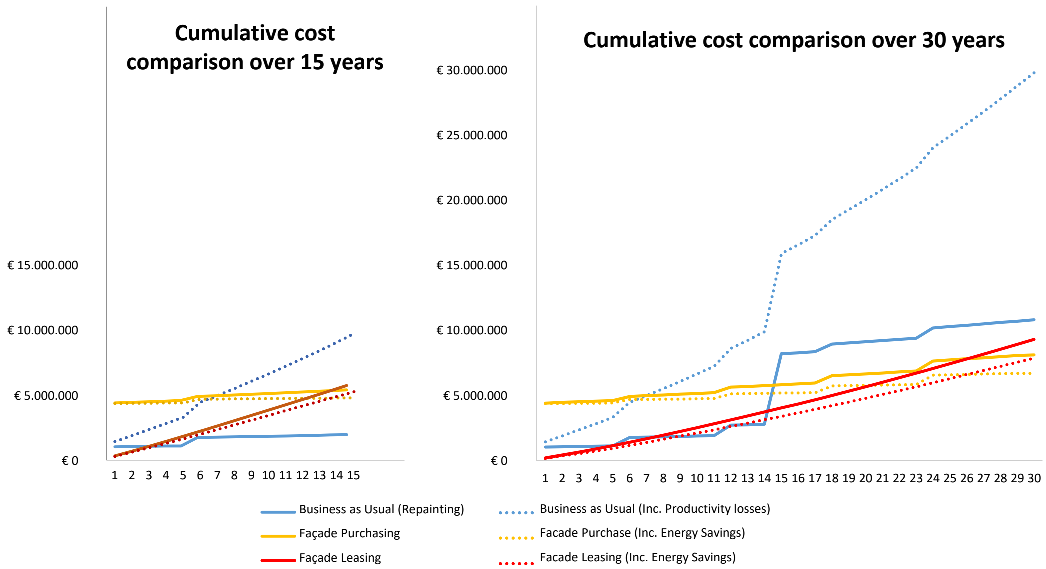

FIG. 7.7 Distributed, cumulative Total Value of Ownership results comparing the three strategic scenarios for the CitG East façade renovation, including selected “soft” values. (First published in: Azcárate-Aguerre, Klein et al. 2020)

The residual value of the FaaS components could not be estimated or considered in the financial evaluation model, and the consulted banks were unwilling to assume any risks related to the residual value of physical components. A more extensive discussion of the rationality behind this barrier can be found in Annex 1: Chapter 7 Results (Extended).

7.4.1.3 Governance and building law

From a policy and legislative perspective, the implementation of PSS contracting models represents a significant change from a status quo built on centuries or even millennia of legal precedence. Innovative and relatively untested contracting models result in an added risk to all parties involved in the PSS project. These risks may translate into disputes during the decades-long contracting periods required from built environment technical components, or which may -and currently does – translate into added complexity and cost of financing.

In the case of The Netherlands, and many other nations built on Western European and Roman law, the rule of accession gives building owners ownership of all fixtures attached to a building, and which can't be removed without damaging the building or affecting its performance. While several models exist for circumventing this legal barrier, these models are based on innovative interpretations of rental and real estate law, and therefore carry a risk in the case of litigation.

A further challenge, once that of legal and economic ownership of physical components is overcome, is the demarcation of technical and financial responsibility over different building components and the technical requirements they aim to fulfil. Of special concern are physical interphases between components (e.g. the structural brackets linking the façade to the building structure) or between interrelated building services (e.g. the interrelation between building façade and heating or ventilation systems when delivering the final energy and user-comfort performance of the building). In the process of breaking down the building unit into its technical systems and performance attributes a chance for new types of disputes exists, when determining who must bear the technical responsibility and the financial expenses related to it.

In the context of the potential legal and financial disputes discussed above, provisions must be made in advance for the potential exit – willing or unwilling – of one or more of the parties contractually collaborating on the PSS project. Over the 10- to 50-year period which a PSS contract in the built environment might span, innumerable events could occur which would result in the exit of a partner or the reorganization or transfer of part or the whole of the PSS structure. These events include corporate reorganisations, mergers and acquisitions, property transactions, bankruptcy of one or more parties, physical damage to the building by unforeseen events (e.g. natural disasters), market fluctuations resulting in chronical building vacancy, and many others. Different forms of financial insurances or technical/administrative securities provided by, for example, industry branch organisations, must be developed and set in place contractually to deal with such events in the most risk-mitigating manner. Some examples of these securities are illustrated in Figure 7.8.

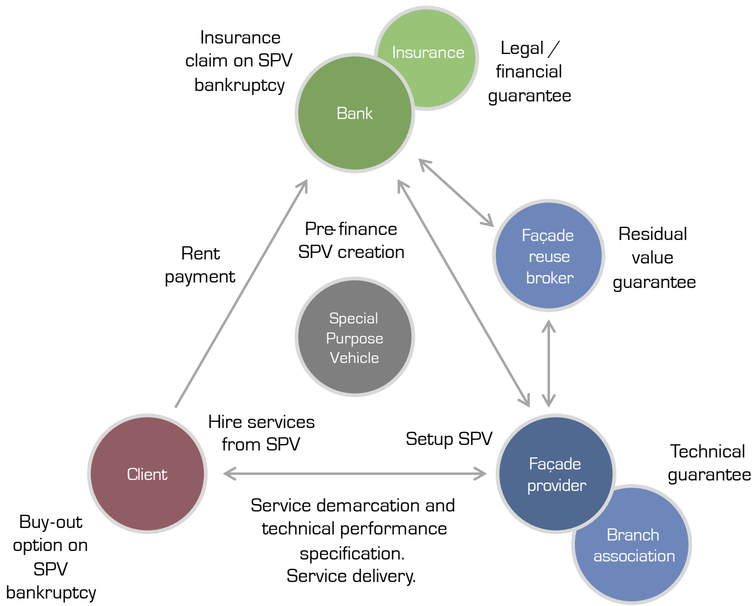

FIG. 7.8 Extended structural diagram of the FaaS "SPV" model, showing stakeholders or contractual/financial products intended to guarantee – and therefore reduce the perceived risks and consequential costs of – a FaaS system. (First published in Azcárate-Aguerre, Klein et al. 2020)

A matter of legal consequence which was unfortunately not addressed by the project, but which was frequently discussed during the planning process, is the organizations of economically feasible reverse logistics chains for the re-manufacturing of used building components. EU regulations are known to limit the cross-border transportation of secondary components, since they are labelled as "waste" which must be treated in its country of origin. This represents a barrier to the economic potential of transporting secondary components to neighbouring EU countries with lower labour costs, where re-manufacturing work could more likely be performed in an economically feasible manner.

7.5 Conclusions

The study set out to test whether the traditional systemic framework for managing, financing, and regulating buildings projects hinder the practical implementation of CE-enabling PSS contracting models. It concludes that, across all the mentioned building-related disciplines, the momentum provided by traditional processes generates a systemic inertia which severely limits the actual decision-making scope of the key stakeholders involved in a construction project. Even in cases in which all stakeholders are aligned from the start in terms of motivations, long-term strategic sustainability goals and willingness to innovate, existing processes largely determine the outcome of financial and fiscal decisions, legal collaboration contracts, building techniques, and managerial organisation. Significant additional effort, motivation, and cost- and risk-bearing is necessary to overcome this inertia. In some cases (such as that of project financing) current practices cannot support competitive PSS alternatives capable of being up-scaled to the mainstream construction market. However, the study has also shown that, at least in the case of the Netherlands, conditions enabling a more mainstream implementation of PSS models could be achieved through targeted action in each of the identified disciplinary fields.

Crucially, results have highlighted the interlinked nature of decisions and innovation pathways across involved disciplines and sectors. In several instances, circular arguments spanning across disciplines block progress for the whole industry. This is a clear indication of the need for orchestrating actors whose role is to coordinate multi-lever action at scale.

Table 7.3 summarises results and main recommendations for the three administrative processes addressed by the study:

Cells in the column summarizing 'Pathway to systemic innovation towards PSS' have been colour coded to represent a feasibility / readiness assessment according to the following legend:

Conditions enabling a more mainstream implementation of PSS models could be achieved through targeted action.
Pathway towards PSS achievable with significant additional effort, motivation, and cost- and risk-bearing to overcome inertia.
Current practices cannot support competitive PSS alternatives capable of being upscaled to the mainstream construction market.

TABLE 7.3 Results and main recommendations for the three administrative processes addressed by the study.

Administrative process	Objectively determinant factor to the success of a FaaS procurement model, color coded to represent result assessment from the study	Main recommendation
Strategic management	Value hierarchy	Significant change in organisational strategy, on both the supply and the demand side of the construction sector: - Supply: Parties interested in the reprocessing must be involved throughout the previous stages of the building´s construction and management to create incentives for resource stewardship or material circularity. - Demand: Client organisation must develop robust investment models based on comprehensive TVO methodologies and must be willing to change their own internal structure to facilitate interdepartmental workflows and budget integration.
	Commissioners' organisational structure	
	Project briefing	
	Contractual organisation (the SPV model)	
	Material circularity	
Project finance	Financial evaluation of the project	Valuation standards must be developed reliably and fairly considering the additional (softer) values of PSS and CE models in the built environment, accounting for externalities which are currently and otherwise borne by society and the environment. Financing models must become broader in scope (considering technical quality, energy-efficiency, or material circularity)
	Transfer tax and Value Added Tax	
	Bankability: Impact on underlying cost of capital	
	Material markets: The problem of guaranteeing residual value	
Governance and building law	Legal framework for value preservation and the argument for concentrated ownership in the real estate sector	Building law must innovate to allow for currently non-standards forms of legal and economic ownership, and of technical demarcation of responsibilities and risk. The concept of building ownership and utility value must be critically revised. Further technical comparison must be made between new PSS and CE models, and more tested forms of collaborative contracting such as DBFMO contracts (Design, Build, Finance, Manage and Operate). A significant barrier is created by EU (and global) waste management policies, which broadly catalogue secondary materials as waste, and limit or fully restrict their transportation across international borders. This makes the economics of material recover unfeasible, particularly in countries with high labour costs were such processes fail to generate subsistence-level value.
	Physical demarcation of materials, components, and systems	
	Technical demarcation of performance, responsibilities, and risk	
	Risk distribution and bankruptcy law	

Perhaps the key challenge highlighted by this study is the broad restructuring and rethinking of the ways in which buildings are developed, managed, financed, and legally protected. The shift from valuing buildings as full functional units, to valuing them as temporary material depositories, puts into question the entire solidity of real estate investment markets. It conceptually forces together the solidity of real estate investment with the volatility of long-term material value speculation. These concepts could arguably be defined more by our culture than by economic reality, and our lack of consideration for the value of materials might significantly change once these materials become scarcer.

7.5.1 Challenges and future perspectives

On the matter of scalability of these results we consider that performance-based models can be an administrative alternative which addresses internal organisation challenges (flexibility and ease of decision-making) and external societal challenges (environmental sustainability). However, their implementation currently faces significant practical hurdles. The hurdles and conditions described are common to different types of real estate owners and project investment decisions around the world. While regional differences exist, the multi-disciplinary approach hereby described and the factors evaluated are expected to be for the most part similar, as are their consequences to CE and PSS implementation. The authors acknowledge that selecting a public entity as client/building owner resulted in specific financial and fiscal conditions which influenced the applicability of the model and the pilot project's outcome. This showcases how the administrative conditions of a building project can be more determinant than the technical specifications of the building. Because of this, the conclusions of this process highlight once again the need for a holistic planning process which integrated all fields of knowledge.

The systemic innovation proposed in this paper could facilitate a shift from Total Cost of Ownership to Total Value of Service. As building technologies evolve, real estate markets fluctuate, and end-user trends change, buildings and their components must be able to adapt to this changing world technically, managerially, financially, and legally, while retaining their value. Solid real estate, inflexible to changes, could be acknowledged as a liability when compared with more flexible and 'liquid real estate' (den Heijer, Arkesteijn et al. 2016). In the story of Theseus' ship, the vessel Is repaired, and components replaced until no physical part of the original ship remains present in the current one. The thought exercise focuses on whether the ship remains the same ship, after all components have been replaced. Questions are rarely asked about the destiny of the removed components, as these seem to be hardly relevant. Theseus' ship is only one temporary application of potentially eternal materials, and therefore should not be our focus of attention. The thought experiment should focus instead on the different vessels, building structures, furniture, and infinite other applications for which the materials in Theseus' ship could be used.

Chapter Conclusions

The chapter concludes that, while FaaS can be implemented within the current systemic context of the built environment, its implementation requires significant investment of additional resources and the acceptance of untested risks.

The financial, legal, and managerial perspectives explored in this chapter can all theoretically lead to a successful implementation of PSS models for façade construction and renovation. In practice, however, the process demands significant customisation of stakeholders' usual modes of operation. This results in added setup costs, the use of customised and untested legal contracts and fiscal models, and the bearing of significant risks by all parties.

Incentivised by the right signals from policy-makers, stakeholders must collaborate in setting up standardised FaaS procurement processes. This includes financial evaluation models which enable FaaS investments becoming tradable financial products, legal contracts built on solid legal building law theory and tested precedent, and client management processes which align with the long-term perspective of FaaS procurement models.

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8 Conclusions and discussion on the Façade-as-a-Service model's applicability and up-scalability potential

Chapter summary

This final chapter provides a critical view on the question of current implementability of Product-Service Systems and other Circularity-enabling business models. Strengths and weaknesses of the research are discussed, and future research and practice paths are identified.

8.1 Conclusions

This dissertation has set out to analyse and understand the motivations and challenges towards implementing Circular Business Models, such as Product Service Systems, within the construction sector in the Netherlands and abroad. Along this path, the systemic, multi-disciplinary nature of the CE transition encounters the complex multi-stakeholder environment typical to the construction industry and the built environment. The systemic innovation required to meet this compound complexity demands the involvement of a multitude of stakeholders (existing and new), and the relocation and redistribution of value and risk between stakeholders in order to economically justify the new individual effort required from all involved parties.

To begin this conclusion chapter, it is crucial to summarise the findings of the six chapters preceding it, and which have built the argumentative body of this thesis. These findings are summarised in Table 8.1, below:

TABLE 8.1 Summary of findings and conclusions per thesis chapter.

Chapter	Research question	Conclusions
2	**How does the current process of building envelope procurement hinder the implementation of energy-efficient and resource-regenerative facades?**	The paper explores how current building (envelope) procurement and construction processes hinder innovation and a transition to a more energy- and material-efficient built environment. It introduces the concept of PSS for building envelope procurement and concludes that the new incentive structure facilitated by a Facades-as-a-Service approach could motivate and accelerate the implementation of energy-efficient building technologies while safeguarding material resources.
3a	**Are decentralised, façade-integrated technologies – and the planning, construction, and management processes behind them – presently capable of delivering the technological solution to the servitisation of the façade industry?**	The chapter summarises the process followed, and lessons learnt from the design and engineering development of an integrated-façade technology pilot project at the TU Delft campus, EWI building. It concludes that - while technological readiness and technical integration has not yet been fully streamlined into an industry standard process - it can be soon achieved with the right market demand signals to promote closer collaboration between the multitude of individual suppliers in the integrated façades value-chain. It establishes that: A. Integrated facades are potentially capable – in certain building typologies - of delivering the holistic, clearly-demarcated technical solution to the PSS model for Facades-as-a-Service. B. The servitisation of procurement processes could in turn promote innovation and supply-chain integration in the integrated facades industry, by allowing technology suppliers to collaborate and have an earlier involvement and a more active role in the façade design, engineering, and planning process. The process also highlighted that technology alone is not the main barrier preventing organic FaaS implementation. Instead, the systemic perspectives of project financing, (demand-side) management practices, and building law must be better understood, since these processes might be responsible for the lack of organic market demand for performance-based solutions.
3b	**Are traditional systemic project development, financing, procurement, and management processes presently capable to adopting PSS alternatives? And can this adoption be efficiently and effectively organised under current systemic processes?**	The chapter summarises the design, engineering, planning, negotiation, and contracting process for a full-scale FaaS renovation project at the TU Delft campus, CiTG building. The process concluded that, while FaaS implementation is technically possible within our current systemic framework, this implementation is by no means promoted or facilitated by current building financing, contracting, or management processes. Rather, our current systemic processes in many ways hinder or prevent the organic adoption of PSS models in the built environment. This by rendering such models more costly, organisationally complex, financially riskier, or more liable to legal disputes. The conclusions of this process contribute to – and are the main foundation for – the thematic areas further explored in chapters 4 to 7 of this thesis.

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TABLE 8.1 Summary of findings and conclusions per thesis chapter.

Chapter	Research question	Conclusions
4	**Which are the main drivers and barriers - from a multi-stakeholder perspective - to the implementation of Facades-as-a-Service?**	The chapter explores the changing roles of the key stakeholders involved in a façade construction or renovation project. It concludes with a list of the key drivers and barriers found which could enable (but presently contribute to preventing) an organic transition towards PSS models and other potentially CE-enabling contracting alternatives. It also concludes that these changes can be achieved within the present legal, financial, and managerial framework. For PSS to become mainstream, however, significant systemic change must be organised in all these disciplines, as the high degree of customization and commitment needed to make it work within the current system will make it unattractive or unfeasible for most stakeholders. Possible solutions to these challenges will be discussed in more detail in the conclusions chapter of this thesis.
5	**What is the role of emerging building technologies on the path towards performance-based contracts and servitisation?**	The chapter concludes that technological development in the field of facades and façade-integrated technologies currently lacks the overarching strategic goal of enabling PSS or CE offers. The focus on a supply-push-based product development process results in suboptimal market reception due to lack of early client involvement or addressing of the building owner's overarching strategic needs (demand pull). Product and process integration, for example through the use of a Façade-as-a-Service contractor with performance contracting objectives, would reorganise the decision-making process behind the market demand for these technologies. Developers and suppliers of building technologies could then work within a defined framework of objectives: To provide effective energy performance and indoor comfort monitoring and reaction equipment to enable the FaaS provider to more reliably and securely provide the performance services for which it has been contracted.
6	**How can the financial performance of a leased versus a purchased scenario be fairly calculated, considering both tangible and intangible costs and values?**	The study presents a new methodology for evaluating the long-term performance of investment decisions regarding façade construction and renovation. This by comparing traditional contracting models versus PSS alternatives. It concludes that, the more robust Total Value of Ownership models become, and the more "soft" values and externalities are taken into account, the more likely PSS offerings are to provide a safer investment alternative over the long-term. Traditional investment evaluation models are limited to only the "hardest" (i.e. most tangibly monetisable) sources of cost and revenue. These models, however, fail to provide a full or fair picture of the impact of the investment decision on the decision-maker himself, on other project stakeholders, or on society as a whole. This shortcoming must be addressed by practical guidelines and regulation in terms of project and real estate valuation, banking and financial applications, and ethical investment practices.

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TOC

TABLE 8.1 Summary of findings and conclusions per thesis chapter.

Chapter	Research question	Conclusions
7	**How do current property development, procurement, and management processes result in linear buildings, and which changes must be implemented at a management and business organisation level to achieve circular real estate?**	The study uses the TU Delft CiTG pilot project as an example of the multiple managerial, fiscal, financial, and legal challenges which come into place when attempting to implement a full PSS contract. It finds that, while a PSS contract is in principle achievable under present systemic circumstances, the process for achieving it is complex and requires significant innovation and commitment from all involved stakeholders. Legal, financial, and managerial practices must be significantly reviewed, and traditional practices must be put into question and reorganised into alternatives more conducive to mainstream PSS implementation. The complexity of this process is currently having an adverse effect on the organic adoption of PSS models, as it leads to additional effort, costs, and perceived risks for the stakeholders involved. Systemic innovation across all thematic topics discussed in this thesis must highlight the added values and risk mitigation potential of PSS alternatives and establish standardised processes to simplify PSS contracting and thus facilitate its mainstream implementation.

Having reviewed the various sub-questions addressed by the chapters in this dissertation, focus can now revert to the broader research question:

– **How can a Product-Service System approach to the contracting of integrated building envelopes be implemented to accelerate the circularity and energy transitions in new buildings and deep building renovations?**

This question can be more effectively approached by breaking it down into the various stakeholder/disciplinary thematic perspectives which have been used throughout this thesis' underlying research. The author presents these perspectives according to a hierarchy of urgency. The effective implementation of PSS models requires interest and commitment from stakeholders across the board. Certain disciplines, however, have a more determinant driving (or hindering) effect on the decision-making structure in the construction sector. These disciplines must innovate first and show a particular commitment to both send a strong signal to the rest of the market and set the practical foundations and precedents to enable PSS implementation.

8.1.1 Sub-conclusion 1: Project finance

— **A lack of valuation standards which fairly consider softer values and "externalities" such as user comfort, energy performance, resource depletion, carbon emissions and other environmental impacts, material circularity, or managerial streamlining, negates an equitable financial foundation on which PSS alternatives can be built.**

Our current financial system assigns small and volatile value to building materials and (pre-owned) components if they are not attached to a functional real estate unit. As an investment or bankable object, the real estate property is perceived by our present culture as far more valuable and secure than the sum of its tangible parts or intangible services. It is a curious and unique feature of real estate objects that, dictated by location, demographics, and other market indicators real estate objects frequently appreciate, even while their technical constituents depreciate. This is a fundamental problem when trying to finance alternative ownership and responsibility distribution models such as Product-Service Systems. The target of financing (the PSS provider) is not the security holder (real estate owner and mortgagee), so that liabilities and securities are misaligned and rest in the hands of different stakeholders. A long-term partnership agreement, in which the building owner co-guarantees the PSS provider's mortgage or business loan repayments, once again assigns all liabilities to the building owner, and defeats the reallocation of incentives and risks at the very heart of Product-Service Systems as Circularity-enabling business models.

Regardless of whether we speak of the commercial, corporate, or public real estate sectors, financial investment evaluation and project bankability are a leading, or at the very least unignorable concern for decision-makers. In this context, real estate valuation practices remain traditional, risk-adverse, and particularly focused on the hardest and most certainly monetisable parameters. A lack of valuation standards which fairly consider softer values and "externalities" such as user comfort, energy performance, resource depletion, carbon emissions and other environmental impacts, material circularity, or managerial streamlining, negates an equitable financial foundation on which PSS alternatives can be built. Simply put: As long as our financial assessment methodologies keep focusing on hard, tangible, short-term cash-flows linear procurement models will always appear cheaper to the individual decision-maker, and are therefore most likely to be preferred by all but the most environmentally-committed or marketing-savvy early adopters.

Real estate valuators and banks must take a leading role in the CE and PSS transition. In the case of the former (valuators), work has been done by (Rooplal Utmani 2021) which provides a detailed account of how Circular Economy values could be considered in the real estate valuation process. Much more work is needed in this direction. In the latter case (banks and other financiers), recent development in the Dutch context set a promising path. At the time of writing, in 2023, an alliance of the largest Dutch banks is establishing standardised conditions when evaluating the bankability of PSS providers wishing to provide performance-based solutions. Such an agreement and standardisation of processes would not only render the financial applications of PSS business models significantly faster, more predictable, and less costly, but it would also facilitate the future trading and re-financing of such contracts between banking institutions. The current impossibility or unpredictability of such transactions represents an important barrier to PSS bankability, as financing is granted (in the cases when it is, in fact, granted) on a case-by-case basis, with relatively short financing terms, and few securities of future refinanceability or up-scalability.

Furthermore in terms of bankability and project finance evaluation, carbon emissions and the opportunity cost of unachieved energy savings must be internalised as project-related societal costs. The rising financial value of material resources must be acknowledged, and material recovery must be internalised as an effective and enforced responsibility of the building (or building components) owner(s) and its financial backers. Banks must extend their involvement in building projects to also include the project renovation or decommissioning phases and establish best practices to avoid material leakage and loss of both real estate and material resource value. Such end-of-service scenarios could be established as contractual requirements for financing, or even better could be considered as positive, risk-mitigating incomes in the project's balance sheet. PSS contracting alternatives must not be seen as an added risk and an uncertainty, but as a different method for organising resources, structuring incentives, and achieving the desired technical and environmental results.

8.1.2 Sub-conclusion 2: Building law and built environment policy

- **The conceptual legal basis for real estate legal and economic ownership must be critically reviewed and updated, and the role of legislation in the safeguarding of real estate and material value preservation must be re-balanced.**

In the (perhaps liberal) opinion of the author, policy and regulation work most effectively when they focus on incentivising long-term value creation or minimising risks of value loss, rather than when controlling (and most likely distorting) markets and prescribing or subsidising specific technical solutions.

The Circular Economy transition differs from the energy performance transition of the 2000's in that it does not aim to enforce or subsidise what is perceived as new project costs (i.e. energy performance renovation costs), but rather highlight new possible sources of revenue, value creation, or value preservation (i.e. optimising facility management processes and recovering rising material residual value). The safeguarding of material resources which are of crucial strategic importance to the state could then be left in the incentivised hands of private actors by reliably monetising the ongoing circular value of such resources. It remains to be seen whether incentives are sufficient for the market change to happen organically. Alternatively, one can envision regulation targeting minimum content of secondary building materials in a new construction or renovation project, or even the setting up of centralised material banks responsible for tracking and safeguarding the flows of materials used in construction and industry.

Our culture has grown used to thinking of ownership as a right, and not a responsibility. The conceptual legal basis for real estate legal and economic ownership must be critically reviewed and updated, and the role of legislation in the safeguarding of real estate and material value preservation must be re-balanced. Regarding the specific models described in this study, contracts must be developed to standardise responsibility and incentive allocation between parties in a PSS contract. Financial incentives in the form of preferential cost of financing must be provided to innovative project consortia which guarantee that technical and managerial processes have been set in place to effectively recover the societal value of secondary materials and reduce embodied and operational energy and carbon. These incentives must be initially evaluated, and later enforced, according to clearly defined Key Performance Indicators.

Fiscal policy must be scrutinised, and the foundations of taxation must be put into question. By taxing human labour over material resources, we are incentivising a culture in which process efficiency in terms of speed of production is more important than efficiency in material recoverability or carbon impact prevention. The "externalities" resultant from these negative incentives do not currently find their way back into the individual building owner's balance sheet, and thus remains a burden on society and on our future material security. Carbon taxes are likely to help, by internalising environmental impact, but it must be evaluated whether such a "penalty-based" approach is the most effective alternative. It will provide a market signal discouraging pollution, but it will not necessarily provide a positive market signal encouraging the equally important and related preservation of material resources. Schemes for carbon-credit trading show a bleak example of how such penalty-based – rather than result- and incentive-based – policies can be circumvented and exploited.

8.1.3 Sub-conclusion 3: Real estate development and management

- **Macro-economic governance models, and micro-economic perception changes, that jointly establish performance-based and/or circularity criteria in building procurement can help motivate more environmentally-efficient decisions by developers.**

Buildings might last decades, or even centuries, but the same cannot be said of the specific commitment of individuals and organisations to these buildings. Few real estate investors and/or operators commit to the future of a building over a planning horizon longer than 10 to 20 years. Changing real estate trends, organisational requirements, investment strategies, and multiple other factors render longer-term thinking increasingly unpredictable, financially risky, and difficult to commit to. It is no coincidence that this same time span is closely tied to property-backed mortgage financing (20 to 30 years), while falling just short of the expected service life of many key building products and systems (20 to 25 years).

From a general sector management perspective this practice of relative short-terminism is not ideal, nor does it lead to a sustainable built environment. The breaking down of the building's 60- or 100-year service life into 15- to 20-year investment cycles creates a tunnel vision – in the eyes of the participants in these short-term cycles – detrimental to longer-term technical or administrative solutions.

Macro-economic governance models, and micro-economic perception changes, can jointly help motivate more environmentally-efficient decisions by establishing performance-based and/or circular management criteria from the time of initial building procurement.

8.1.4 Sub-conclusion 4: Technology

— **The technology to produce energy efficient and circular buildings exists, and the technical requirements of a Circular Economy transition are increasingly well-understood. What lacks is a long-term management frame through which to first be able to choose the more circular solution, and then enforce that this solution remains effectively circular over the decades-long time-frame in which the built environment operates.**

The real estate sector and the built environment are demand-driven. We do not build because developers, contractors, and system suppliers want to build, but because society needs buildings to operate, and investors can create value by supplying these buildings. Exceptions to this rule, such as the supply-based development of commercially unreasonable housing projects in the United States shortly before the 2008 financial crisis, fuelled by the irresponsible handling of sub-prime-mortgages, highlight the risk of supply becoming disconnected from demand.

When financial and regulatory standards are in place to incentivise Circular or Servitised solutions over traditional linear contracting, the architecture of decision-making for commercial, corporate, and public actors is likely to change into a more levelled field. Until these standards are in place, most decision-makers will continue to be limited to what banks will finance (upper decision-making limit), and what regulation allows (lower decision-making limit).

Technology is not the driving force behind construction, and the industry's attempt to act like it is continues to produce disappointing results in terms of low mainstream technology integration, insufficiently improved building stock performance, and a rising technical complexity which requires ever more specialised planning consultants and facility managers. Technology must instead be seen as an enabler of what the market (driven by financial and regulatory boundaries) should be motivated to request. It can also inspire new trends and applications by continuing to push the boundary of what can be technically achieved. This as long as critical focus is given to the fulfilment of clear strategic goals and the broader systemic challenges we currently face. The technology to produce energy efficient and circular buildings exists, and the technical requirements of a Circular Economy transition are increasingly well-understood. What lacks is a long-term management frame through which to first be able to choose the more circular solution, and then enforce that this solution remains effectively circular over the decades-long time-frame in which the built environment operates.

8.1.5 Guidelines for a circularity-enabling critical re-thinking of the real estate construction and management process

Whether we speak of Product-Service Systems or of other Circular(ity-enabling) Business Models, the basis for their effective circular operation is the creation of sufficiently robust supporting processes. These processes must be set in place from the start of the construction process, and combine a legal, financial, technical, and managerial strategy spanning the entire service-life of the project. This is illustrated in Figure 8.1, below.

The process begins and ends with the Project evaluation, which questions the fundamental and minimum material requirements of the project, collects information on available recoverable legacy resources, and/or re-evaluates and inventories circular contracting options for new material inputs. The following procurement, construction, operation, monitoring, and re-/de-commissioning stages are undertaken in close collaboration between the real estate contract manager and the service providers responsible for different building services or layers.

Regulation and finance must secure the key transition points (marked as arrows) in which governance structures or financing mechanisms currently create a responsibility or incentive void. Financing must be connected to the real estate asset or be connected to the material resources during their reprocessing stage. In this sense financiers can only step out of one of these project stages once another investor has been found to provide continuity into the next one. Financing can therefore not only focus on the better years of a construction project, while the project is in full operation and before any major renovations are needed, without considering end-of-service transition into material- or component-based finance.

Governance must also support these stages: First, policy incentives can nudge decision-makers towards more circular choices. Preferential financing or fiscal benefits would be some financial incentive options and would leverage the interest of regional government to co-invest in material resources as a matter of future regional security. Second, regulation must focus on performance criteria which include measured energy use, measured user comfort, and ease of material recovery. Throughout, but specially at the re-/de-commissioning stage, material resource governance must secure material stewardship and avoid land-filling or down-cycling.

Figure 8.1 highlights the fact that circular supply-demand collaboration must be supported by systemic processes of building law and financing. This is particularly the case in the transition moments which are determinant to effective circularity: At the commissioning moment in which the commodity value of raw materials and manufactured building components is transferred into the (performance) value of the real estate they become part of. At the decommissioning moment, when the inverse happens, and unitary real estate value must be broken down into the commodity value of now secondary raw materials.

An analytical framework for the implementation of PSS alternatives in the built environment

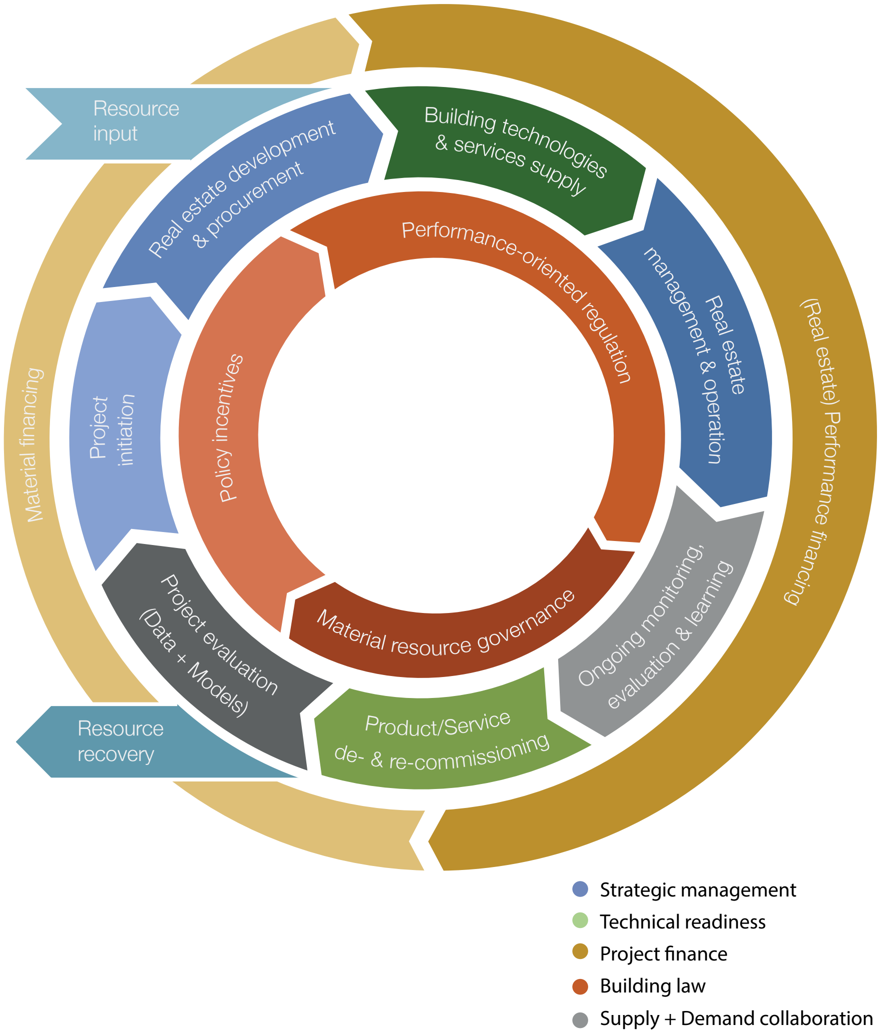

FIG. 8.1 Ongoing collaboration diagram showing the close interaction between supply and demand, facilitated and delimited by project finance and building law, which could enable effective circularity in the built environment.

8.2 Discussion and reflection

Nearly a decade has passed since the author first explored the concept of Facades-as-a-Service as part of his MSc thesis. In the early 2010's energy efficiency and carbon impact mitigation were still the focus of research. Circular Economy theory was yet to become a mainstream topic, at least in the built environment, and was mostly absent from academic discussions and university curricula. At the time of publishing, in particular in the case of the Netherlands, the Circular Economy has become a common household term. Manufacturers of consumer products, automobiles, and even building components increasingly offer and market "Circular Products" as alternatives to their traditional linear counterparts.

One of the key take-aways from this thesis should be that "**Circular Products**" can not be manufactured and may not be purchased, leased, or even hired as a service. "**Circularity-enabled Products**" may be produced, which account for the technical and economic steps necessary for the eventual recovery of material resources, but products on their own can never be effectively circular. Effective circularity can only be achieved through the circular operation, management, and eventual highest-value recovery of materials. It is therefore tied to complex decision-making and administrative processes which must be set in place at the time of procurement, and which must span the entire decades-long service-life of the product in question. A "Circular Product" can end its life in a landfill, while a "Non-Circular Product" might be effectively recovered and enjoy multiple effective service lives.

The tightening of real estate markets, and the rise in interest rates in the aftermath of the COVID-19 pandemic are likely to have an unexpected influence on the attractiveness of PSS offerings: On the one hand, the difficulty of investing in real estate (due to historically high property prices and rising interest rates) might open the door to new forms of investment, such as investing in building layers for already existing real estate objects. On the other hand, the rising cost of capital, together with the insufficient valuation standards previously described, will render PSS offerings increasingly unjustifiable and even unaffordable from a project finance perspective. This will be specially the case if we continue to consider the value of material virtually negligible.

A new (niche) generation of consumers and decision-makers is growing, which recognises the aesthetic and environmental value of recovered components and materials. In the case of construction, a trend can be recognised towards a scarcer use of unnecessary claddings and finishings, a practicality in easier access to installations and the exposing of structural and technical equipment as something with an intrinsic aesthetic value, which does not need to be covered by superfluous layers of unnecessary material.

These trends are, however, limited to a certain sector of society in specific geographical regions. It is still insufficient as a systemic solution to the global resource management problem and - in many instances - it reflects a market wish to “circularity-wash” old product offerings, rather than fully understand the fundamental systemic changes required to achieve effective long-term circularity.

Despite growing societal and commercial interest in Circular Business Models and Product Services Systems as alternatives for a more sustainable construction sector, organic adoption of such models in real cases and pilot projects has been limited. Only a handful of projects exist which have implemented circularity not only in products but also in management processes. These cases are still limited to a premium group of the real estate sector, and have by no means “trickled down” to the mainstream built environment.

The ease with which human societies – in particular wealthy ones – have been able to source material resources over the last few generations has made us forget that these resources are a crucial component of a region’s current wealth and future security and sustainability. Controls on the use of these material resources have been placed in effect in the past, for example during the world wars in Europe in the 20th century.

Such extreme conflict scenarios should not be necessary to modify our views on the value of materials. Instead, we should pre-emptively question our strategic approach to our future resources and ask ourselves whether – if the resource emergency was more pressing or more visible – we would approach the problem in radically different ways.

Would we continue to transfer material ownership simply as an afterthought of an economic transaction? Would we create national or regional material banks, from which resources can only be rented (not purchased) but to which they must eventually return? Would we peg the value of currencies - like we did in the past with the gold standard - to the collective value of these regional material banks? Would we continue to forbid the transfer of “waste” into our border, and the sale of high-quality primary resources to other regions of the world?

While some of these questions and scenarios might sound extreme, they help illustrate different approaches to our management of material resources. With the benefit of foresight, we are collectively aware that resources are not finite, and that their value and significance is only likely to increase. This gives us the opportunity to re-evaluate the ways in which we technically, legally, and financially manage these resources, and gradually shift it towards a more sustainable alternative before we are forced to do so in an emergency.

In the context of PSS and CE the fundamental purpose of the different disciplines involved in the creation and operation of the built environment must be questioned and adjusted, so that more efficient models can be created for the delivery of holistically well-performing buildings. Table 8.2 below shows some examples of this fundamental reconceptualization. While exploring each one of these topics is well beyond the scope of this thesis, it does conclude from the work performed that such questions must be addressed in the transition towards a more energy- and resource-resilient future.

TABLE 8.2 Examples of fundamental strategic changes from the perspective of the four disciplines studied.

	Traditional approach (Linear)	Question	New approach (Circularity- / PSS-enabling)
Real estate development and management (demand)	To initiate, coordinate, and deliver functional real estate space.	What is the role of the real estate developer?	To initiate and organise ongoing real estate enabling processes, adaptive to market demands and societal needs.
	To balance and optimise real estate-related financial or utilitarian income against (rents and property value) against ongoing expenses (commissioning of maintenance, replacement, renovation services, and decommissioning).	What is the role of the real estate manager?	To manage building system performance contracts and maximise utility value in order to optimise potential real estate income from finite spatial resource.
Project finance	Direct and tangible expenses and values.	Which factors determine the bankability of a building project?	Traditional + Intangible and external costs and values. Flexibility to face uncertainty.
	M^2 of functional space, depreciating (in the case of building components) and appreciating (as a general spatial trend, location-dependent)	What is the functional unit being financed?	Yearly cost per m^2 of functional area. $X = €/m^2/yr$ or ((Initial investment + residual value) / operational years) + (land appreciation / operational years)
	Depreciating asset requiring additional periodic maintenance investment and ending with a one-time decommissioning cost.	How is material resource value reflected in the project's balance sheet?	Independent investment object with fluctuating material value (according to commodities market), requiring ongoing life-extension servicing and ending with a regenerative decommissioning value.

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TABLE 8.2 Examples of fundamental strategic changes from the perspective of the four disciplines studied.

	Traditional approach (Linear)	Question	New approach (Circularity- / PSS-enabling)
Building law	The static, spatial functional building unit, irrespective of technical condition or environmental impact.	What is the predominant unit of societal value which must be safeguarded by building law?	The utility value of real estate space delivered per unit of environmental-impact adjusted embedded material (m^2 of functional space per m^3 of CO_2- and CE-adjusted material content per year)
	Real estate property is private, materials embedded are private.	How do we assign ownership of real estate and its components?	Real estate property is private, the materials embedded in it are under loan from society.
Building technologies and construction management processes (supply)	Physical building components capable of fulfilling technical building requirements (guaranteed over an initial period significantly shorter than the expected effective service life).	What is a (building) product or system supplier responsible for delivering?	Contracted performance metrics in terms of user-oriented requirement per unit of time.
	Engineering optimisation balancing initial component cost (i.e. production + overheads) and robustness (i.e. maintenance cost and service life expectancy).	How can a system supplier maximise added value provided?	Strategic service-life planning, balancing of tangible material products and intangible services and upgrades. Allow for flexibility, expansion, and contraction of building services and layers.

From Total Cost of Ownership to Total Value of Access

The last decade has seen a gradual but still relatively slow increase in the number of PSS solutions offered or (fully) implemented in the construction sector. Investment project evaluation would appear to remain a significant barrier to PSS implementation, specifically due to the lack or insufficiency of benchmark data against which such offerings can be fairly compared. Just like real estate valuation practices remain for the most part focused only on certain hard costs and values related to the real estate object, real estate investment evaluation remains focused only on specific, direct, and hard building costs and (realised or unrealised) revenue sources. Project commissioning in the construction sector remains for the most part structured into initial investment costs (at the time of construction or renovation) and ongoing maintenance costs. Better-organised commissioners schedule these maintenance moments and build a financial reserve over time with which to address such expenses. These schedules might also take into account internal organisational management costs and other expected expenses such as decommissioning costs, unexpected upgrades or replacements, et.

Total Cost of Ownership, which is slowly becoming a common term in real estate management, refers to the sum of all expected liabilities resultant from different possible real estate investment decisions over time. It must be highlighted that such evaluation models rarely look beyond direct and internal project costs, and avoid externalities, so that they should actually be called Total *Internal* Cost of Ownership. Only when accounting for so-called *externalities* such as energy consumption and source, life-cycle environmental impact and embodied carbon of materials, material circularity potential and effective realised circularity, among other factors can we actually speak of an *overall* Total Cost of Ownership. The focus of a TCO methodology on liabilities springs from the fact that liabilities, in particular hard, direct, technical liabilities, are more tangible and relatively easier to predict. The current cost of a new construction or a building system renovation can be established with a fair degree of accuracy through a bidding process. Meanwhile, the current market price of replacement and maintenance services can be projected at a discounted rate over time, until the expected end-of-service moment of the respective component, in order to build a sufficient reserve fund to cover such cost when the time comes.

Total Value of Ownership (also known as Total Benefit of Ownership) aims to estimate also the added organisational or personal value delivered by one investment decision over another. Values, however, are much more subjective than costs, and much more likely to change over time or between one building owner and the next. Real estate transactional value and rental value can be estimated by valuators according to market conditions such as location and macro-economic environment, and building characteristics such as state of repair and (deferred) maintenance, energy-efficiency, facilities provided, et. Beyond these basic commercial values or sources of potential revenue, real estate values become increasingly subjective or abstract, and difficult to estimate and account for specially when projecting these values and their relative relevance into the future. Values such as energy-efficiency, user comfort, architectural branding (for example for a large bank's corporate office aiming to project an image of power and stability through a clean architectural design and high-end finishings) are difficult to estimate. They can only be roughly approximated based on statistical analysis of past trends, as we would do in corporate finance when trying to calculate the value (in hopefully added sales) delivered by a marketing campaign.

The (still ongoing) impact of the COVID-19 pandemic on commercial property value showcases the difficulty of establishing a reliable and enduring value system. Almost literally from one day to the next the entire concept of workspace was disrupted, and its necessity questioned. And value is, above all, a measure of societal necessity resulting in market demand. Many companies are still trying to define a strategy for dealing with the remote-working options made available by technologies and practices developed during the COVID-19 emergency. These strategies vary widely, from improving the quality of the real estate (i.e. office spaces) to motivate workers to return to presential working schedules, to an overall shrinking of the real estate space to facilitate only a few presential meetings and activities, while shifting the bulk of the organisation's working practices to a remote and virtual environment. A Total Value of Ownership estimation made of an office real estate object in 2019, which would have not accounted for such exceptional circumstances as a global health emergency, would have surely given very different results from a similar study of the same object in 2023. Flexibility in use, both technical and regulatory, and a capacity for quick and economic conversion into residential, warehousing, or any other real estate activity with a persistently higher demand, would have likely become one of the key sources of value to the real estate owner during this period.

So far the focus on these methodologies has been on "Ownership", as ownership is the traditionally most usual and risk-adverse way of accessing the values and benefits delivered by a real estate object, while (unfortunately) also assuming its liabilities. Ownership, however, is a broad topic which encompasses a range of scenarios: From full legal and economic ownership gained through a 100% equity transaction, to complex divisions of legal and economic ownership based on project finance structures involved several diverse sources of equity and debt financing. While real estate ownership has been traditionally seen as a net positive in terms of financial security and appreciation, rental revenue, and utility access, the rising complexity of buildings and the uncertainty of external factors (e.g. extreme climate events, financial cycles, tightening building codes and regulations, changing fiscal policies, et.) are bearing down on the liability side of the Total Value of Ownership scale. These personal or organisational risks, combined with the social cost of suboptimal energy efficiency and material resource management, highlight the need to critically re-think preconceptions around (the value of) real estate ownership and investment evaluation.

A Total Value of Access methodology can be envisioned, in which the real estate operator is no longer the owner (in the traditional sense) of the physical components of the building, but is instead responsible for the procurement and management of several building layer and building system contracts. It becomes a flexible bridge between the supply side of the construction sector (i.e. builders and system suppliers) and the demand side of the real estate sector (i.e. building tenants and end-users). Changes in building demand volume or technical requirements no longer become direct liabilities to a traditional building owner who has not yet reached the financial break-even point of an investment decision. Instead, such changes can directly translate into a downsizing of building capacity and/or characteristics, with building components being released from short-term performance-based contracts, and relocated to other building where they are more needed (see Figure 8.2). The building's end-user has access to the building it needs, the real estate operator has access to the building components it needs to deliver functional and high-value space to the end-user, suppliers have access to the financial, material, and human resources needed to deliver functional spaces to the real estate operator on an ongoing performance-based basis, and society can retain access to the resources it has made temporarily available to the system suppliers in order to deliver these functionalities.

Such a reorganisation might seam extreme and economically unlikely, but it is the role of science to question current models, and to propose and analyse new and potentially more efficient ways of organising and deploying resources.

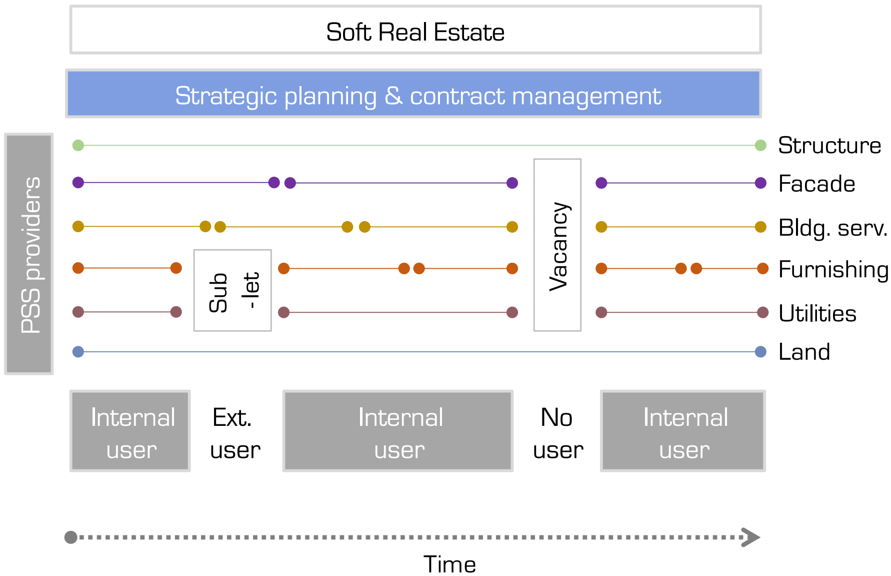

FIG. 8.2 Diagram of the “Soft real estate” process enabled by the ongoing provision of building layers-as-a-service. Total Value of Access evaluations can be performed by the real estate operator, bridging and balancing the changing demands of end-users and the developments in building technologies.

8.3 Scientific relevance

The urgency of industry-oriented practical research aiming to motivate or implement short-term societal change forces a re-evaluation of the scientific research process and scope. The separation between disciplinary fields of knowledge, which has been necessary to categorise and organise human experience and scientific development over the last centuries, has often brought with it the disadvantage of inter-disciplinary dis-connectivity and over-specificity. In other words, in the pursuit of more effective ways of organising resources, we frequently run the risk of missing the forest - of sustainable developmental objectives - for the trees of clearly delimited academic and practical disciplinary fields.

The systemic innovation proposed by Circular Economy and Product-Service Systems theory requires a systemic understanding of the multi-perspective changes, motivations, and solutions needed for a conscious and controlled evolution capable of meeting and addressing our increasingly urgent environmental needs. The multi-disciplinary analytical framework described in this thesis aims to contribute to the CE and PSS transition debate by highlighting the interrelations between disciplines, and the determinant effect these interrelations have on our macro- and micro-economic decision-making capacity. Some disciplines are by definition more closely tied than others: Technological capacity in terms of hardware must be examined in close relation to the management of this technology in terms of strategic perspective and functionality (software), so that the implementation of state-of-the-art technology can be limited or even avoided by improving our operational algorithms and end-user's understanding of available technologies. Building and corporate law and project financing are also closely related, with concepts such as legal and economic ownership having been built over centuries or millennia as a way of motivating investment and growth while encapsulating and distributing risk.

In the scientific and practical development of effective circular solutions through PSS business models it is crucial to begin at the largest possible scale and with the broadest disciplinary lens. This to avoid effects, external to the specific discipline being considered or prioritised, capable of undoing or cancelling the intended positive results. The engineering of building products which are easier to disassemble of re-manufacture must follow from an understanding of the interests and incentives which will impact this building product throughout its decades-long service-life. Financial and legal models must not only protect the investor's interests, but motivate and if necessary force both investors and suppliers to collaborate in ways that safeguard the valuable materials to which society has limited access.

8.4 Societal relevance

It is unquestionable that the resource management crisis presents a significant challenge to our global society. This challenge is particularly pressing in the built environment, which consumes and contains the largest fraction of the world's material resources.

Individual decision-makers, particularly at a retail, owner-occupier level, cannot be expected to make radically innovative, system-changing choices which flow contrary to the traditional financing, legal, and technical processes dictating the development of the construction sector and the built environment. This thesis has presented a model for implementing Product-Service Systems on building envelopes in the Netherlands. The lessons learnt, and challenges identified, can be extrapolated (accounting for regional and cultural differences) to other building layers and geographical regions. These changes will first require a group of highly committed and mutually trusting stakeholders, willing to explore solutions in full-scale commercial pilot settings. Once such examples are proven to be successful, large public and corporate decision-makers can follow, making centralised decisions on large buildings or building portfolios. Only once these models have been well-developed, understood, and standardised, can we expect the average retail investor or owner-occupier to make different decisions at a sufficiently large scale.

The topic of the CE and PSS transitions in the built environment is a hugely complex and intricate one. Throughout this research it has been necessary to maintain a broader, systemic view of the thematic fields involved, and the interaction between these fields, rather than a closer, in-detail dissection of each thematic area. This thesis has focused on identifying the practical drivers and barriers to implementation, it has also listed potential solutions, but it has not elaborated on these solutions or defined whether such solutions are the only possible ones. This would have been outside of the thesis' scope and beyond the disciplinary field and biases of the author.

The work presented in this thesis shows how the CE and PSS transitions (or the lack thereof) are the mechanical result of inertia and friction between interacting multi-disciplinary parts of our present societal organisation. It aims to highlight the relevance of broad-spectrum systemic thinking when considering Circular Business Models or PSS offerings. I hope this systemic perspective will motivate and support more in-depth focused individuals - from the various disciplines discussed and many others - to continue working on this topic and finding innovative and creative solutions to promote the long-term sustainability of human industry and the built environment.

8.5 Reflection on effectiveness of Action research methodology

The action research methodology employed in this study was instrumental to motivate stakeholders in practice, preoccupied with the daily operation of their organisations, to get involved in a systemic research project aiming to significantly overhaul traditional ways of working and collaborating in the construction and real estate sectors. The role of the researcher and research team, within such a methodology, becomes frequently ambivalent, and there is a constant danger of crossing the line between experimental research and observation, and active promotion and development of the research, its pilot prototypes, and its possible commercial applications.

As stated by Melrose (2021) regarding the role of the PhD researcher involved in Action Research (AR):

The postgraduate student is often more driver (through the various AR cycles), facilitator, recorder, and writer than others in the group. The topic of practice and theory building for an AR thesis must be sustainable by the student through the duration of the research project, even if the group of participants changes with the cycles. Self-reflection on learning and progress as an action researcher and/or practitioner is an important part of the thesis.

Reflecting on this process, I am convinced that an action research approach was necessary, and was the only way to engage, collaborate with - and acquire commercially and legally sensitive information from - the multi-disciplinary stakeholders involved. Product-Service Systems were not a new idea at the start of this research project, they had been in existence for decades, and several companies across multiple sectors had implemented them with varying levels of ambition and success. Accessing information on these cases, however, and extrapolating conclusions from such cases to the (façade) construction and real estate sectors was a challenge. Companies involved in practical PSS research would do so with the intent of gaining a competitive advantage by differentiating their value offering from that of their competitors. Data provided by such studies would therefore remain anecdotal or superficial, and it would be nearly impossible to access specific data such as project contracts, financial evaluation and structuring, or effective material circularity rates.

This research project started from a challenge not to evaluate whether FaaS models would be an effective material circularity strategy, but whether they would be effectively feasible at all. No pilot prototypes or sample projects existed, nor in fact do they exist yet at the time of writing. The research therefore had to evaluate the model, while at the same time being actively engaged in developing and testing this model. This results in a limited scope of conclusions, and several shortcomings in terms of quantifiable outcomes, but it is a necessary step to "kick-start" a development process which is not taking place (quickly enough) through organic market mechanisms. The research is aimed to provide a general foundation to this field of study, with the hope that the several projects and initiatives resultant from, or inspired by, this research will be able to generate more specific data from the different disciplinary fields explored. Some recommendations for these future research paths are provided in the following section.

8.6 Future research trajectories

Below is a list of questions that arise from this work, and which aim to motivate experts from other related fields of research in the search for solutions to the identified barriers. How can we measure the effective circularity and carbon avoidance of Product-Service System offerings?

- How can we make scientific assumptions on the future management of present material flows, with technologies we are not yet aware of and accounting for economic realities we might not yet understand?
- How do building law and fiscal policy incentivise or hinder the contracting of PSS alternatives in the built environment?
- How can we modify the concept of ownership to grant secure rights but also underline social responsibility to future generations?
- How can policy incentivise material recovery through mechanisms that investors and building owners are incentivised to embrace, rather than circumvent?

- [Further work required on] How can real estate valuation standards be developed which integrate softer, less tangible costs and values, internalise environmental and economic externalities, and account for residual value of components and material which will become available only decades in the future?

- What is the role of governance in the securing of future regenerative material flows?

- How active must governments be in the securing of these flows through new forms of legal and economic ownership which highlight material stewardship responsibilities?

- Should regional central material resource banks be created, which loan materials to the public and private parties that need them, with the condition that they must eventually return?

While many of these questions have been to some extent addressed by this thesis at a broad systemic scale, it is important that experts from each discussed field of knowledge perform a further, more detailed, and more technical assessment of the barriers and opportunities for implementation.

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Glossary of terms

AEC	Architecture, Engineering, & Construction
CBE	Circular Built Environment
CE	Circular Economy
CRE	Campus Real Estate (TU Delft)
CREM	Corporate Real Estate Management
DAS	Designing an Accommodation Strategy
DBFMO	Design, Build, Finance, Maintain, & Operate
DfD	Design for Disassembly
DR	Discount Rate
EEE	Electrical and Electronic Equipment (Sector)
EoL / EoS	End-of-Life / End-of-Service
ESCo	Energy Service Company
E(S)PC	Energy (Savings) Performance Contract
FaaS	Façades-as-a-Service
FM	Facilities Management
HVAC	Heating, Ventilation, & Air Conditioning
IRR	Internal Rate of Return
JV	Joint Venture
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
MEP	Mechanical, Electrical, & Plumbing
NVP	Net Present Value
OCC	Opportunity Cost of Capital
OEM	Original Equipment Manufacturer
PPP	Public-Private Partnership
PSS	Product Service Systems
RoI	Return on Investment
SME	Small and Medium Enterprise
SPV	Special Purpose Vehicle
TCO	Total Cost of Ownership
TVO / TBO	Total Value of Ownership (a.k.a. Total Benefit of Ownership)
VAT	Value Added Tax (BTW in Dutch)

Appendix

Results Chapter 7 (Extended)

The following table presents a more extensive collection of results organised according to each administrative process identified. Cells in the column summarizing 'Pathway to systemic innovation towards PSS' have been colour coded to represent a feasibility / readiness assessment according to the following legend:

Conditions enabling a more mainstream implementation of PSS models could be achieved through targeted action.
Pathway towards PSS achievable with significant additional effort, motivation, and cost- and risk-bearing to overcome inertia.
Current practices cannot support competitive PSS alternatives capable of being upscaled to the mainstream construction market.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative proces	Management	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Value hierarchy	The nature of the building project's commissioner's activities has a determinant influence on the prioritisation of values. For commercial property developers and owners, the building itself is the core business activity: a positive balance between hard values (operational income) and hard costs (operational expenses) is a necessary condition to render the project feasible from a business and finance perspective. In the case of corporate and public real estate the building is an operating asset used by the organisation to fulfill their core business processes or public services. This allows organisations in such segments to look beyond hard values and costs, and consider also softer factors such as strategic fit, sustainable performance, staff productivity, social goodwill, branding and sustainable perception et. A non-extensive list of factors, and their generalised prioritisation in different property segments, has been shown in Figure 7.3.	
Commissioners' organisational structure	The traditional linear project flow – which consists of the development, management & exploitation, and decommissioning phases–- is deeply ingrained in the real estate discipline and the structure of building-commissioning organisations (see Figure 7.4). This structure is adopted by both commercial and corporate or public real estate, even though the first will tend to have several owners throughout the building service life, while the second tend to keep ownership throughout. Development teams are in most cases different from facility management and decommissioning teams. This leads to a conflict between initial cost short-terminism, long-term cost-effectiveness, and circularity requirements.	

	Pathway to systemic innovation towards PSS
	The question is how to evaluate the impact of these soft values reliably and fairly on a project's Total Cost (or Value) of Ownership. This will be discussed in the following section on financial parameters.
	Strategic and organisational barriers were addressed in a relatively organic fashion, as evidence emerged of the need to innovate across several traditional organisational processes. Budgets allocated to different TUD departments (project development, maintenance, facility management, central university finance, and end-user faculty) were integrated into a single CiTG East façade whole life-cycle project budget. A project manager was appointed capable of bridging the multiple organisational departments. The project manager's experience as a technical building consultant enabled him to negotiate the FaaS service agreement with the FaaS provider, shifting the procurement process from the prescription of technical solution to an agreement based on functional requirements, including sustainability and circularity. A link was created between the FaaS provider, and the facility maintenance company awarded years before with a contract for the maintenance of the entire TUD campus. Part of the budget allocated to the maintenance company was transferred to the FaaS provider, since the CiTG building's East façade is no longer part of the TUD maintenance provider portfolio but instead serviced by an external party (the FaaS provider). The processing of user complaints and the adjusting of the East façade's smart technical operational algorithm is done jointly by both companies, and then discussed in open sessions with focus groups representing facility management and the faculty end-users. The smart façade technical systems algorithm controls operating conditions for the façade's external sun-shading system and night-cooling system and is therefore determinant to the correct functioning of the façade in relation to the technical service requirements established in the service agreement, such as user comfort.

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TOC

Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative proces	Management	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Project briefing	The procurement process is not only defined by the strategic priorities / objectives, value hierarchy, and organisational structure of the project commissioner (the problem-owner), but it is bounded by the range of possible solutions the market presently offers. In the case of performance-based procurement, as with other innovations, this pull/push mechanism between demand and supply often results in stagnation and a “circle of blame” in which suppliers do not offer product-service combinations that commissioners are not asking for, while commissioners do not ask for such combinations because no suppliers are (reliably) offering them. Gielingh and co-authors (Gielingh 2008, Gielingh, de Ridder et al. 2008) make a distinction between the functional requirements needed by the building owner and end user, and the technical solutions offered by suppliers to fulfill these requirements. Several authors on project commissioning theory have highlighted the drawbacks in project briefing processes being too technically prescriptive, resulting in inefficiencies such as: – Suppliers and products become commoditised, as the scope provided for innovation or added value are largely restricted by the commissioning process. – The focus of the transaction is on the delivery of the prescribed physical products (and the embedded material resources), rather than the ongoing and efficient fulfillment of the desired performance requirements. – The resulting building is a static, depreciating object, inflexible to changes in technology, market or user demands. – Service-life performance, End-of-Service scenarios, and residual value of components are not factored into the decision-making process.	
Contractual organisation (the SPV model)	Traditional project structures rely on the contracting party–- generally a real estate developer or operator–- securing financial resources to initiate, retrofit, maintain, etc. a construction project. Resources are secured usually through a property-backed mortgage, depending on the type of client, acquired through public fiscal funding (public and semi-public clients), corporate revenue, equity, and debt (corporate clients), and project financing through equity and debt (commercial clients).	

	Pathway to systemic innovation towards PSS
	The FaaS pilot project showcased both sides of the innovation push/pull argument: to enter a full PSS contract, on the one hand TUD's commissioners had to integrate the scope, expertise, and budget of the project development and facility management teams, and even of the end-user faculty, in order to provide a complete list of functional requirements. On the other hand, a clear demarcation had to be found on which factors the FaaS supplier consortium could be held liable for. For example, in the case of energy consumption and user comfort, Faas supplier consortium would not bear the risk of energy price volatility, performance of the central building energy system, and extreme weather events. A full list of unbearable risks related to the functional requirement was negotiated. It must be stressed that some of the performance limitations could be attributed to the fact that only one of the building's facades had been renovated, so that guaranteeing performance over the whole building's functional requirements (e.g. energy consumption and indoor comfort) was impossible. It would be expected that such limitations would not apply in the case of a full building envelope PSS intervention.
	In a full Product-Service System model the contracting party prefers not to have legal and economic ownership of the operating assets but would rather outsource these to the third-party service provider. The current system of building law and project financing cannot easily deal with such a proposition. An asset with a relatively long service-life, such as a façade, is not an easy object to finance for a bank or leasing company, as they would with industrial or office equipment with shorter (<10-year) service lives. – The financier would have to commit to a 50-to-70-year financing period (the usual service-life of a façade). Alternatively, a shorter financing period could be agreed, but re-financing risk would have to be borne by the building owner. In the absence of a refinancing option the building owner would be forced to purchase the façade, and the PSS model would become ineffective and its circularity potential lost. – A second option would be for the FaaS provider to arrange the financing, essentially becoming a building envelope developer. However, façade companies are usually SME's, with limited loan-bearing capacity and a corporate and financial structure meant for manufacturing and/or assembly, and not for real estate investment. During the early stages of the project, it was concluded that most façade builders (except for perhaps the largest multinational companies) would be unable to finance and keep in their balance sheet more than a handful of FaaS projects. This solution would therefore lack scalability. The solution found, as summarized in the Figure 7.5 diagram**.** diagram, overcomes these contractual and financial barriers by integrating bank, client, and FaaS provider with a fourth stakeholder: a Special Purpose Vehicle (SPV), created in most likelihood by a real estate investment and management fund used to dealing with long-term building projects. The SPV would act as a mediator between the collaborating partners. It would retain legal and economic ownership of the façade, arranging financing and managing the service contract with the FaaS provider in the final interest of the building owner (client). The SPV can retain a long-term planning horizon, knowing that the facade will probably remain in place for decades, but otherwise brokering a new location where it can be installed. Building owner, financier, and even FaaS provider can be replaced if the building is sold to a new owner, the first financing term concludes, or the FaaS provider faces bankruptcy or stops providing façade services for any reason.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative proces	Management	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Material circularity	The key circular value proposition in the built environment is to convert a building owner's 'liability' to manage their building materials in a circular way, into a financial incentive or an asset for the providing entities. Retaining, maximizing, and extending the value of materials indefinitely by applying re-life options with both 'retroactive' and 'proactive' circularity leads to positive long-term spill-over effects, such as stabler supply and value chains, savings in pollution taxes / fees., preventing loss of end-of-service value, etc. With 'retroactive circularity' we can define the circular End-of-Life management of legacy equipment already installed on current buildings. The building owner must traditionally hire a demolition or deconstruction company to remove the materials before a replacing building system can be installed. Most often buildings are demolished, leading to significant 'material leakage' and loss, but in some cases, they will be deconstructed in a way that material value can be recovered. With 'proactive circularity' we can define the development of new technologies capable of more efficiently enabling fully circular material reprocessing. It must be noted that existing technical solutions (i.e. framing systems and façade-integrated technologies) are already quite capable of allowing certain degree of updating and reprocessing, so that the field is ripe for this transition.	

	Pathway to systemic innovation towards PSS
	In the case of the CiTG building, the existing façade included asbestos (as was usual at the time of construction), so that the deconstruction of the façade was not practically possible. A company was found with a new method for separating asbestos from steel, however their processing plant was under construction and would not be ready for another 2 years, during which time TUD would remain legally responsible for the correct management of the asbestos-containing steel frames. This was considered too high a risk by the commissioner, and the decision was made to traditionally dispose of the equipment in a way that is safe but prevents the recovery of the contaminated materials. The CiTG project's relatively small scale and tight construction schedule made it impossible to develop and integrate new technical solutions for a more circular façade system in time, however, the consortium involved in the project, together with other industry parties, continued working on these technical challenges and developed the Ciskin façade system beyond the scope of the project (Alkondor, De Groot & Visser et al. 2022).

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Project finance	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Financial evaluation of the project	Traditional project-financing investment evaluation, which is at the heart of a project's decision-making process, aims to limit risks by focusing on the "hardest" values and costs expected from a construction project (see Figure 7.3). In recent years the discussion around Total Cost of Ownership (TCO) and Total Value of Ownership (TVO) has emphasised the relevance of softer values and liabilities.	

	Pathway to systemic innovation towards PSS
	In the FaaS project an intermediate TCO/TVO method was pursued, in which a hard factor evaluation would lead the decision-making, but an estimate of selected soft values would be provided as supporting input. The evaluation thus included a cash-flow and a TVO analysis, both studies we performed with planning horizons of 15 and 30 years. In the case of the 30-year study it is assumed that the façade will have to be replaced on year 15. This as it is unrealistic to assume that an already 60-year-old and technically inadequate façade system can remain in place for an additional 30 years, no matter how frequently it is given minimum maintenance. The results of the cumulative TVO calculations can be found in Figure 7.6, while the cumulative distribution over time of the TVO results have been shown in Figure 7.7. First, the results illustrate the wider reason why deep energy façade renovations are failing to reach mainstream volumes. When looking at a 10-20-year planning horizon (as most building owners do), the decision to perform minimum maintenance and defer larger decisions to a later date is supported by the financial case. In the case of commercial real estate this is exacerbated by the likelihood that the current building owner might decide to sell the property before a mayor renovation point is reached. Only when soft values and the estimated opportunity cost of suboptimal user comfort are considered, does the business case support a decision to renovate sooner rather than later. Second, result show that a PSS model is not necessarily more expensive than a traditional linear model from a long-term TVO perspective. While externalised financing and maintenance costs make the PSS alternative more expensive on a yearly basis, avoiding the need to invest capital upfront frees up building owners' resources which can be used for alternative projects with their own (potential) financial returns, while still providing the added values of a retrofitted façade. Thirdly, borrowing conditions resulted a difficult barrier to overcome. As a public organisation TUD has access to direct government borrowing at preferential rates, so that financing the project via a commercial third party (the SPV FaaS provider) would involve a higher Cost of Capital. The value of material circularity of the new façade could not be considered as part of the financial model because no bank would consider the residual value of the façade in their project financing model. This resulted in an additional increase in the FaaS model's Total Cost of Service (TCS). As a result of these two factors the TCO analysis, from the building owner's perspective, was not in favour of the FaaS model. Conditions would have been expectedly different for a commercial building owner (for whom Cost of Capital is generally higher, and more similar to what the SPV FaaS entity could apply for). Conditions could have also improved if the residual value of the façade was considered in the project's financial evaluation. After reviewing these results, the building owner TUD decided to undergo a deep energy renovation, but not to finance it through PSS because as a publicly university they did not expect a significant financial performance from an alternative investment, rendering one of the key values behinds a PSS model invalid.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Project finance
Objectively determinant factor to the success of a FaaS procurement model	**Current situation**
Transfer tax and Value Added Tax	Tax policy is highly dependent on geographic region. Even within the European Union, despite general trends and shared basic concepts, each member state has different rules regarding construction projects and real estate property taxation. This is highly related to the country's building law ideology (more on this below). For this reason, the analysis below is provided for illustration purposes of the Dutch case, and as a regional example of how fiscal policy can affect the implementation of circularity-enabling PSS. In the case of The Netherlands, a general distinction is made between: A. A building's construction (or renovation) phase, during which materials and labour are being commissioned for the project which are eligible for a Value Added Tax (VAT), which in the Netherlands is 21% (with some exceptions); and B. A building transaction involving a finished and functional real estate object, which can be an entire building or a fractional part of it (e.g. a flat in an apartment block). In this second case, in the Netherlands, a transfer tax of 2% for residential buildings and 6% for non-residential buildings is applied[2].

2 As a result of the ongoing Dutch housing crisis these values have changed, and exceptions have been created since the period during which the CiTG project was ongoing. These changes are not directly relevant to the present study, but they would influence the extent to which fiscal policy could hinder a FaaS model. Transfer tax is not charged if less than 6 months have passed between a previous ownership change and a new one, in which case the buyer in the second transaction will cover the transfer taxes paid by the buyer in the first transaction. Thus, can double transfer taxation be avoided, but it must be paid when more than 6 months have passed between the first and second transfer.

	Pathway to systemic innovation towards PSS
	Several tax advisors provided conflicting views on how the Dutch tax authorities would react to the question of transfer tax in the PSS scenario. However, no references could be found in either literature or case law, rendering the question open until the Dutch tax authorities ruled a decision on the matter. This would only happen if a decision to procure a FaaS system was first made by TUD, and the Dutch tax authorities were asked to rule on the fiscal consequences of the decision. A. In a traditional construction project a 21% VAT would be applied to the cost of materials and labour delivered by the façade supplier to the building owner. In the case of a PSS model, the 21% VAT would be deducted by the FaaS SPV (as a commercial business expense), and would therefore not be charged to the building owner up front. Instead, a 21% VAT would be charged on the monthly FaaS service fees charged by the SPV to the building owner. B. According to most fiscal advisors consulted, once the first fabricated façade modules are being fixed onto the building, then the building owner will automatically become legal owner of the façade panels. If the FaaS supplier was to become legal owner after construction has started, then transfer tax must (most likely and in most cases) be paid. To avoid additional taxation and considerable costs therefore the FaaS decision must be made before the façade construction process (on site) is initiated. Some tax advisors suggested that transfer tax would not be applicable if the façade was transferred to the FaaS SPV before the project officially concluded and technically delivered, but this could not be verified until it was implemented (resulting in a 6% risk for TUD over the entire new façade's transactional value). The risk of transfer tax being due applied significant pressure that the SPV's corporate structure, financing application, and contractual definition were finalised before the CiTG's East façade was technically delivered. This process was impossible within the remaining time-frame, exacerbated by time constraints established by the CiTG façade's technical replacement planning, and its strict delivery deadline before the end of Q4.2020. This resulted in an unknown and unexpected risk for TUD as commissioner and was a crucial point in the final decision not to implement a full PSS model for the CiTG façade renovation.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Project finance	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Bankability: Impact on underlying cost of capital	The valuation of a building is of primary importance to the building owner, regardless of whether the owner is a commercial, corporate, or (semi)public party, because it will determine its effectiveness as collateral in a loan application. In the present economic system, the value as collateral of real estate is among the most secure guarantees a lender can have, and thus contributes to lower interest rates than other types of collateral securities. If the loan is not serviced then the building can be foreclosed and, except during downturns in real estate cycles, the principal on the loan can be for the most part recovered by the lender. Organisations of all types use the value of their owned buildings as collateral to secure low-interest loans. A broad difference exists, however, in the loan conditions (e.g. loan terms and interest rates) accessible to different types of organisations. Commercial organisations have a higher risk profile since the building itself is at the core of the clients' business model and its source of revenue. Loss of income related to the building's operation would lead to incapacity to service the loan. As a result of this, loans tend to be for a shorter period and involve a higher interest rate. Corporate and (semi)public clients, meanwhile, have additional sources of revenue, since the building is only an operating asset facilitating their core activities, and are therefore more secured borrowers. Loan terms will be longer and interest rates lower, in particular for (semi)public organisations able to borrow directly from the government at national central bank rates. As part of their due-process obligations, valuators are responsible and liable for following existing valuation standards and securing to the financial institution aiming to guarantee the loan that the collateral value of the building has been correctly assessed. As a result of this, valuation standards and practices are generally risk adverse, and slow to change.	

Pathway to systemic innovation towards PSS

The building façade is usually around 20% of the initial cost of a building project, while a building- for most purposes- is not usable if it doesn't have a façade. To what extent would externalising the façade legal and/or economic ownership affect the value of the building as collateral was the subject of significant academic and professional debate in the FaaS project.
In the case of the CiTG façade, no valuator could commit to a final response, but rather three arguments emerged which are summarised in the table below. Most likely, as in the case of taxation, whether the building owner kept (or could easily contractually recover) legal and/or economic ownership of the façade would also determine how the FaaS construction would be treated in a valuation assessment.

Factors that lead to a conservative view regarding valuation standards

Arguments	Description
The higher project cost of a FaaS alternative would result in a lower debt-bearing capacity of the building owner.	As the monthly costs of a PSS are higher than in a purchased façade, while the gains from an alternative investments are most likely not considered in the building-specific financial evaluation linked to the project's bankability.
This higher project costs could be positively counter-balanced, in a valuation, by the gained benefits to the building and its occupiers.	Improved quality and performance of the building, energy savings, and user comfort. All these factors would contribute to a higher transactional value of the building and therefore would render it a more valuable guarantee as collateral.
The legal model used to commission the FaaS would have an impact on the (split) ownership of the building, and therefore the building's value as collateral.	Due to the uncertain nature of the legal model in the case of a dispute, as will be described below, and the lack of precedents in either legal literature or case law, a certain and final answer could not be provided.

The risk of lost value as collateral, while not fully confirmed, was deemed to be manageable, even in the case that the SPV model removed legal ownership of the façade entirely from the building owner. The loss of physical material value of functional unity would be offset by the higher building utility and transactional value. Also, the long term of the eventual FaaS contract (15-30 years), would mean that even in the case that the building was sold the FaaS contract (and the underlying façade) would be transferred with it and the building's functional unity would be preserved.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Project finance	
Objectively determinant factor to the success of a FaaS procurement model	**Current situation**	
Material markets: The problem of guaranteeing residual value	The fundamental philosophy in states with a European systemic heritage, which underlies building law since its roots in Roman jurisprudence, is that buildings are financed based on their value as a complete functional unit. As such, they can be used as collateral to guarantee a loan, in other words mortgage-based financing. This loan, however, will always have a shorter term than the expected service life of the building. The lender does not want to assume any risk over the maintenance of the building by its owner/manager, or over the building's End-of-Life (EoL) scenarios. The loan must thus be fully repaid before major renovation reinvestments or EoL processes are to be reasonably expected which would lead to a change in the utility value of the building. In the current construction market, the residual value of materials found in buildings is therefore of no positive consequence to financial or real estate markets, which means that it does not contribute to the value of the building as collateral when securing a loan. In most cases, it does not even provide the building owner with an expected recoverable income at the time of decommissioning. In fact, most frequently, building owners will need to pay for the demolition and removal of used or obsolete components, so that the removal costs remain a liability which should be considered in the balance-sheet of the building owner.	

	Pathway to systemic innovation towards PSS
	It would not be an exaggeration to define the treatment of buildings as material banks as a fundamental paradigm shift in the context of real estate financing, and thus a determinant factor on the evolution of the built environment. To account for the residual value of materials, the financier would have to essentially *invest in the future value of secondary material markets.* This last sentence summarises the extent of the risk perceived by a potential lender: – *Future value:* Which in the case of buildings and building components must be projected several decades into the future. – *Secondary materials:* Meaning that long-term forecasts and assumptions must be made regarding recycling and reprocessing technologies, social and cultural views on reuse of components and materials, evolving building technologies and practices, and several other trends and factors. – *Material markets:* Which are generally volatile, but which have seen particularly unprecedented fluctuations as a result of recent crises such as the ongoing COVID-19 pandemic and the consequences of geopolitical conflicts and tension (World Economic Forum 2022). Also, several studies have shown that long-term material value trends have changed, and in fact reversed, since around the year 2000, so that no long-term historical data can be counted upon during the financial evaluation (Ellen MacArthur Foundation 2013). This is probably the most essential and complex question in the transition towards circularity in the built environment: How to combine low-risk investment in real estate with high-risk investment in building materials? Unfortunately, the answer to this question is far beyond the scope of this paper. While several discussions were held on the matter with diverse financiers during the FaaS project, and several positive arguments were presented, no final consensus could be reached. None of the financiers consulted would consider a loan longer than a traditional mortgage, nor would they consider a positive balance in the project's cashflow as a result of the potentially recoverable value of (potentially more circular) components and materials.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Governance and building law	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Legal framework for value preservation and the argument for concentrated ownership in the real estate sector	The "rule of accession" provides ownership of all immovable structures and fixtures to the owner of the land or structure on to which they are fixed. This is the case not only in the Dutch context but throughout a large part of the world, across countries whose governance has been influenced by Western thought, and whose legal codes have been fundamentally inspired by the Roman legal system (Van der Walt and Sono 2016). As stated by (Ploeger, Prins et al. 2018): "the purpose of property law is to offer legal security and to minimise transaction costs and to maximise and preserve real estate values in society". The argument for concentrated ownership is therefore based on the concept that the whole is more valuable than the sum of its parts, and that a real estate object is more likely to lose value or face transactional disputes if ownership of its essential components is divided among several legal entities with diverse or even conflicting economic interests. With the rising complexity of buildings and building systems, the essential nature of any individual component can be disputed. The law has therefore focused on a broad definition of essential components as "fixtures", or any component that is physically attached to the building and whose removal would result in significant destruction or loss of key functions.	
Physical demarcation of materials, components, and systems	Van der Plank & de Jong (2019) recognise a distinction between tenancy (apartment) law and lease law. The former implies legal ownership of a functionally independent unit (such as an apartment within a residential block), even when the provision of certain key functions (e.g. circulation areas and central heating) are collectively owned by the community of owners. Lease law, meanwhile, deals with economic ownership (i.e. right of use) of a technically definable but not necessarily functionally independent object. Right of lease is in principle unrelated to the spatial and functional integrity and autonomy of the leased unit. As long as a clear physical distinction can be made between those buildings, systems, or components which are owned by the landowner, and those which are being leased from a third party, a right of leasehold should be definable. The complexity of such a definition could become a challenge in the case of building systems which are not spatially contained but are instead widely integrated throughout the building (i.e. centralised builder service installations).	

	Pathway to systemic innovation towards PSS
	In the context of applying PSS models to the construction sector, as has been discussed by (Chao-Duivis 2018) and (Ploeger, Prins et al. 2018), the argument for split ownership of building layers and systems clashes with the legal framework under which the real estate sector has been traditionally regulated. It is however desirable, as the retention of legal ownership - by the service provider - of any tangible material products needed to deliver an intangible performance service will provide the additional legal and economic incentives to effectively reprocess materials and components through reuse, repair, re-manufacturing, and/or recycling activities (Baines and Lightfoot 2013, Stahel 2016). In the FaaS project, the challenge of legal ownership was considered addressed with sufficient certainty and risk-avoidance when the model was proposed in which the FaaS provider would rent the contact points on which the façade would be connected to the structure, from the building owner. A right of leasehold could be established by which the building owner would lease from the FaaS provider the façade, while the FaaS provider would install the façade on the contact points that it in turn rented under a long-term contract, thus avoiding the automatic transfer of legal ownership under the rule of accession. While not certain until its first potential litigation (in the future), the model was considered sufficient by legal academic and practice experts. Contractual allocation of technical responsibility and risk was the focus of another research group. This resulted in the development of a detailed technical service agreement in which were established the scope of activities which the FaaS provider had to perform, and the contractual reaction time within which these activities must be performed. A distinction was also made between expected maintenance against natural wear and tear, and special maintenance resulting from incorrect engineering, manufacturing, or user behaviour. Such special maintenance, determined on a case-by-case basis, would still have to be addressed within the contractual reaction time, but it might not be covered by traditional product guarantees, nor by the FaaS service agreement.
	Lease law is most frequently applied to horizontal surfaces, for example leasing a plot of land for a defined period to erect a temporary structure on it. In principle, however, the cited authors find no fundamental reason or precedent preventing such a construct from being applied to vertical surfaces as in the case of a façade, which has been the case for the FaaS project. The challenge of physical demarcation was illustrated by the case of a state-of-the-art façade system with high service integration: The curtain wall – which consists of framing, glazing, paneling, and other potentially integrated decentralised components such as solar shading, actuators, or BiPV units – could be clearly defined as a self-contained physical object. The interface between the curtain wall and other building elements (e.g. structural brackets or supporting timber framing), could be included or excluded from the leased system, but will most likely also be leased together with the curtain wall. Probably the biggest challenge to this physical demarcation lies in cabling (e.g. electricity and ICT) and piping (e.g. heating and ventilation), which could in many cases be largely interconnected with the centralized building services infrastructure. As the PSS in FaaS was only partially implemented (as a service contract without lease), this aspect was left unresolved.

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Systemic innovation pathways required for each determinant factor towards PSS for building projects.

Administrative process	Governance and building law	
Objectively determinant factor to the success of a FaaS procurement model	Current situation	
Technical demarcation of performance, responsibilities, and risk	Technical performance in traditional product-based offerings is largely constrained to limited warranties against certain types of defects in manufacturing or installation. These warranties tend to be limited to several years, typically below the expected service-life of the product, thus essentially transferring a large part of the component's operational failure risk to the client.	
Risk distribution and bankruptcy law	Entering any legal relation as established by a contract presents opportunities and risks which must be carefully assessed by both parties. The case of a contractual relation expected to last decades, means, for example, that the individuals representing the organisations which have entered the contractual relation will no longer be part of these organisations by the end of the contract. Such contract lengths are not unprecedented but are most often found in relatively simple agreements involving governmental and non-governmental organisations, such as for example a 100-year land lease awarded to a building owner who does not own the land on which the building stands.	

	Pathway to systemic innovation towards PSS
	As we approach “result oriented” PSS offerings (Tukker 2004), the definition of technical performance expands to include not only the technical integrity and direct output of these components, but the final operational outcome which the system should deliver to the client’s processes. In the case of a “functional result”-based FaaS contract (the highest level in Tukker’s categorisation) the expected contribution of the façade to the client’s processes would be the delivery of a specified energy performance (or savings against an initial benchmark), the delivery of a determined indoor comfort, and ensuring a certain degree of circularity. In such a scenario it is easy to envision several contractual arguments emerging: - Interaction between the façade system and centralized building services: in most buildings, the delivery of indoor comfort is the result of interaction between the building envelope and integrated decentralized systems and centralized building services (such as ventilation, lighting, heating and cooling). This division could lead to an uncertain demarcation of performance responsibility between contractors, or between components owned directly by the owner and those being leased or hired under a performance contract. - User behaviour and user preference: documentation of the role of user behaviour on actual energy savings (i.e., after a deep building energy renovation), show the potential disruptive effect of negative user behaviour on final energy performance. This could lead to conflict between provider and client regarding the reason for not achieving the expected energy performance. As mentioned in Task 3, these aspects resulted in partial implementation of PSS for the façade of the CiTG building. In theory, with full envelope PSS, these aspects could be overcome.
	In the case of a FaaS contract, parties will seek securities to protect them in case any of the other stakeholders wish to voluntarily exit the agreement or are forced to exit by unforeseeable events such as bankruptcy. Such securities don’t exist in the current construction and real estate market and had to be developed during the CiTG project. Referring once again to the SPV model previously described some of these guarantees are illustrated in Figure 7.8, and described below. – A façade reuse/re-manufacturing broker can facilitate the transaction between one FaaS contract and the next, so that a FaaS system removed from a building can be adjusted to fit onto another one. Such parties are starting to emerge in the Dutch context. In fact, a party was found who was willing to purchase a future buy-option on the FaaS, so that it would have the right to purchase the façade at a given time in the future for a certain price. This option was not attractive in the CiTG case because TUD would in most likelihood want to continue contacting the façade for a longer period. Also, a buy-option is not an obligation for the buyer to purchase, while it is an obligation for the seller to sell, so the concept was considered too risky. – Since the loan for financing the project would be granted to the FaaS provider (consortium), it would not be guaranteed by the client’s building. Meanwhile, as described above, the value of the façade is uncertain. In order to secure servicing of the loan several (combinable) options were explored: A financial insurance on the loan servicing, granted to the FaaS provider, but eventually paid for by the building owner as part of his FaaS fees; a buy-out option (or obligation) in which the building owner would purchase the façade from the FaaS provider (and thus pay the lender) in the event of the FaaS privider’s default; and a FaaS take-over option in which the defaulting FaaS provider could be replaced by a new party, who would essentially purchase the FaaS SPV and its assets from the original consortium. – In terms of technical guarantees that the FaaS system would continue to be serviced, even in the event of the Façade Builder’s bankruptcy, the Dutch Metal Façade Branch Organisation would commit to finding a new party willing to take over the contract with the SPV. The new party would then continue to perform technical maintenance on, as well as end-of-service processing of, the FaaS system.

Curriculum Vitae

Juan Francisco Azcárate-Aguerre (1986) is a business and real estate developer, building technologies engineer, and architect. His work focuses on the intersection between building technologies, construction economics, and real estate management, with a particular attention given to the practical micro-economic aspects of the Circular Economy and clean energy transitions in the Built Environment.

His background is in architecture (B.Arch 2005-2010, Universidad Iberoamericana, Mexico City, MX), during which time he transferred to the Southern California Institute of Architecture (Sci-Arc, 2008-2010, Los Angeles, California, USA). Between 2010 and 2012 he worked as Building Information Management (BIM) and façade engineering consultant at Gehry Technologies, the technical complex project development branch of Frank Gehry's architecture studio. He then went on to study an MSc in Architecture, Urbanism and Building Sciences, in the Building Technologies track (2012-2014, TU Delft, The Netherlands). In this programme he started integrating his personal interest in real estate and construction management and building economics in his MSc thesis "Façade Leasing" (precursor to "Facades-as-a-Service"). From 2014 to 2022 he (co-)acquired and worked on several research and online education projects at TU Delft, focusing on the business and decision-making aspects of the Circular Economy transition in the Built Environment. Between 2018 and 2023 he worked also as PhD researcher at TU Delft, developing most of the content of this thesis.

In parallel, since 2015 he co-founded – and later became sole director of – Gearcraft Real Estate, a real estate investment, redevelopment, and management firm specialising on energy- and carbon-efficient commercial and residential properties in the Randstad region of the Netherlands. In this role he redeveloped the 1907 former district courthouse building in the city centre of Delft, integrating energy efficient technologies in a Dutch national monument, while piloting Product-Service Systems contracts and financing for the kitchens of the 16 residential apartments created in this heritage former public services building. The PSS contracts used were among the tangible outcomes of the FaaS projects at TU Delft.

Since 2022 he has shifted sector, and is now Managing Director of Reflek Technologies Europe, a global supplier of specialised coatings for automotive, maritime, and architectural applications. In this role he is responsible for strategic brand development, and for establishing the European sales and distribution operations of the company. He still dedicates some of his spare time to consulting and lecturing on Product-Service Systems and Circular Business Models, the rest he dedicates to hiking, reading, cooking, and traveling.

He lives with his wife in South Tyrol, Italy.

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Facades-as-a-Service

A cross-disciplinary model for the (re)development of circular building envelopes

Juan F. Azcárate-Aguerre

Facades-as-a-Service (FaaS) is a systemic innovation model aiming to accelerate and enhance the energy and comfort performance improvement of our buildings, while safeguarding the availability of material resources for future generations. The circular economy and clean energy transitions in the built environment have respectively dominated the academic dialogue in architecture, engineering, and real estate over the last decades. While significant progress has been made, and many fine examples of more sustainable architecture exist, the process has been hindered by traditional systemic models for the planning, contracting, financing, construction, and management of building projects. If we are to meet the ambitious climate-change mitigation goals and material resource preservation challenges of our generation, it is crucial to re-think the way in which we build, operate, and decommission the built environment. Product-service systems (PSS) are a promising model for realigning environmental risks and responsibilities with financial and business objectives, while promoting much deeper and long-lasting collaboration between all parties involved in a building's life-cycle.

This thesis focuses on the building envelope, as one of the most performance-determining systems in our buildings. It then questions the technological, managerial, financial, and legal contexts which often perpetuate unsustainable linear practices despite the urgency for - and technical feasibility of - more energy- and resource-efficient alternatives. Facades-as-a-Service is a topic that extends far beyond technological readiness and architectural engineering. It is rather a thesis about how we make façade construction and retrofitting decisions, the systemic parameters that determine and constraint these decisions, and whether – in the search for a more sustainable built environment – we should question the fundamental concepts behind these decisions. The results show that gradual and strategic development with a multi-disciplinary perspective can enable and facilitate the implementation of more efficient and sustainable building practices.

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