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Doctoral Thesis in Planning and Decision Analysis

Decision support for the implementation of low-carbon measures in the building sector

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Abstract

The building sector is responsible for about a fifth to a third of global greenhouse gas (GHG) emissions. Therefore, a successful mitigation of GHG emissions over the entire life cycle of buildings is particularly important to achieve climate targets such as the Paris Agreement. This requires measures at multiple levels and from multiple actors, including broad roadmaps for the building sector, policies and regulations, certification and green procurement criteria, and new practices among property owners, architects, developers and manufacturers. Such initiatives are sometimes supported by the introduction of tools and methods to quantitatively assess environmental performance. Life cycle assessment (LCA) is one such tool, used in certification and increasingly in procurement and regulation. To reliably steer towards lower environmental impacts, environmental performance assessment tools need to be precise, accurate and well-adapted to the decision contexts in which they will be used. While a tool like LCA can provide valuable decision support, some methodological issues remain unresolved, and its effect in real decision situations remains understudied.

This thesis aims to support decisions and initiatives to mitigate environmental impacts in the building sector, with a particular focus on fulfilling ambitious climate targets. The thesis addresses two facets of this overarching issue. First, it investigates challenges to the implementation of relevant sustainable practices, at various levels and in various decision contexts. Second, the thesis considers to what extent environmental performance assessments could steer towards low environmental impacts (and in particular low global warming potential (GWP)).

The thesis is based on a combination of quantitative and qualitative approaches. At a strategic level, a quantitative model of buildings' GWP linked to four backcasting future scenarios is used to spotlight issues for the fulfilment of ambitious climate targets. This helps challenging existing paradigms and images of the future about how buildings are constructed and operated. At a more operational level, multiple qualitative studies explore barriers to specific practices to mitigate environmental impacts, and the roles played by environmental performance assessments. An interview- and workshop study explores important factors for the adoption of space sharing, as a way of optimizing the use of indoor space. A survey-

and interview study highlights challenges to the use of requirements by Swedish municipalities to promote low-GWP construction. A third interview study shows how various artefacts mediate work with sustainable design in housing projects. Finally, the thesis addresses more directly the accuracy of environmental performance assessments, and investigates how choices of data and method related to maintenance and replacement affect LCA results, exemplified for façade materials.

The modelling of buildings' GWP in backcasting scenarios helps challenge current paradigms by drawing attention to some less-discussed issues, such as reducing embodied emissions (including by avoiding new construction) as well as the demand for indoor space. Space sharing can help optimizing the use of indoor space, but several factors limit its adoption. It requires different practices among building users and property managers, including different business models and performance metrics considering occupancy. Ambiguities in national legislation and municipal plans regarding the status of shared and multifunctional buildings also hinder space sharing initiatives (e.g. unclear rights and responsibilities of tenants and property owners, conflicting requirements for fire safety or ventilation, etc.). Similarly, the thesis highlights important regulatory ambiguities regarding to what extent municipalities can set requirements to promote low-GWP construction. Environmental performance requirements in construction also entail barriers related to limited in-house skills, access to data, time and resources. Using such requirements would first require bridging skill and data gaps. Similar barriers are highlighted regarding the use of LCA in public housing projects. In such projects, artefacts such as national regulations, local development plans and internal requirements of the housing organization enforce a certain level of work with sustainable design while limiting the range of design options. Other artefacts simplify the design work and provide standardized default options. In such cases, design choices that strongly influence environmental performance are taken upstream of the project, when these criteria, requirements and default options are developed.

The thesis highlights ways in which quantitative assessments of environmental performance could directly influence building design and management, e.g. through the introduction of environmental performance criteria in regulation and procurement. Besides challenges related to skill, data, time and resources mentioned above, the thesis draws attention to the variability of LCA results due to choices of method and data sources.

In the particular case of maintenance and replacement processes, the choice of reference study period (RSP) influences the relative significance of these processes, and longer RSPs favor more durable products. Discrepancies exist between different sources for service life data, indicating a need for more reliable data. The use of a round-up or annualized number of replacements makes little difference in average, but can lead to different outcomes in specific cases. This shows a need to carefully harmonize methodological choices as LCA becomes used more and more broadly in procurement and building regulation.

Furthermore, the thesis also draws attention to more complex effects of environmental performance assessments in housing projects. Widespread certification systems can become de-facto definitions of sustainability for actors, influencing design even in projects that are not certified. Environmental performance assessments can hide or reveal certain aspects of sustainability. Widely used assessment tools can act as “black boxes”, where criteria for what constitutes a sustainable building are hidden and no longer contested. This process helps operationalize sustainability in building projects. However, it can lead to some important aspects being disregarded. For instance, conventional energy performance metrics are often normalized for floor area, ignoring occupancy and space efficiency. On the other hand, quantitative assessments can also highlight important aspects of the multifaceted issue of sustainability. The thesis exemplifies this by using a quantitative model of buildings’ GWP to draw attention to key mitigation strategies, and by reviewing energy metrics highlighting occupancy and space efficiency.

Keywords: building, sustainability, environmental performance assessment, life cycle assessment, decision making

Sammanfattning

Byggsektorn står för mellan en femtedel och en tredjedel av globala växthusgasutsläppen. En framgångsrik minskning av växthusgasutsläppen under byggnaders hela livscykel är därför väsentlig för att uppnå klimatmålen, såsom Parisavtalet. Detta kräver åtgärder på olika nivåer och av olika aktörer, inklusive övergripande färdplaner för byggsektorn, policies och regelverk, kriterier för certifiering och grön upphandling, samt ny praxis bland fastighetsägare, byggherrar, arkitekter och byggmaterialtillverkare. Ibland stöds sådana initiativ av verktyg och metoder för kvantitativ miljöbedömning. Livscykelanalys (LCA) är ett sådant verktyg som används för certifiering, och i ökande grad i upphandling och regelverk. För att styra mot lägre miljöpåverkan på ett robust sätt måste miljöbedömningsverktyg ha god precision och vara väl anpassade till de beslutssammanhang där de ska användas. LCA kan ge värdefullt beslutsstöd, men vissa metodfrågor återstår fortfarande, och det saknas kunskap om hur användning av LCA kan få effekt i verkliga beslutssituationer.

Denna avhandling syftar till att stödja beslut och initiativ för att minska miljöpåverkan inom byggsektorn, med särskilt fokus på ambitiösa klimatmål. Avhandlingen undersöker två aspekter av denna övergripande fråga. För det första utreder den utmaningar i relation till genomförandet av relevanta hållbarhetsinitiativ inom byggsektorn, på olika nivåer och i olika beslutssammanhang. För det andra utforskar avhandlingen i vilken utsträckning kvantitativa miljöbedömningar kan styra mot lägre miljöpåverkan (och särskilt klimatpåverkan).

Avhandlingen bygger på en kombination av kvantitativa och kvalitativa studier. En kvantitativ modell av byggnaders växthusgasutsläpp nyttjas på en strategisk nivå i fyra framtidsscenarier med backcastingmetodik, för att belysa viktiga aspekter för att nå ambitiösa klimatmål. Modellen bidrar med att ifrågasätta befintliga paradigm och framtidsbilder om hur byggnader byggs, förvaltas och används. Ett antal kvalitativa studier undersöker hinder för några specifika hållbarhetsinitiativ på en mer operativ nivå, samt vilken roll miljöbedömningar kan ha för dessa. I en intervju- och workshopstudie undersöks viktiga faktorer för delning av byggnadsytor, för att optimera deras användning. En enkät- och intervjustudie understryker utmaningar för svenska kommuners användning av miljökrav för att främja byggande med låg klimatpåverkan. En tredje intervjustudie visar hur olika

artefakter medierar arbetet med hållbar design i bostadsprojekt. Slutligen undersöker avhandlingen precisionen i miljöprestandabedömningar och visar hur osäkerheter och metodval relaterade till beräkning av underhåll och utbyte påverkar LCA- resultat, exemplifierat för fasadmaterial.

Modellering av byggnaders växthusgasutsläpp i backcasting-scenarierna bidrar till att ifrågasätta befintliga paradigm genom att peka på ett antal mindre diskuterade klimatstrategier, såsom behovet att minska inbyggd klimatpåverkan (bland annat genom att undvika nybyggnation) samt minska efterfrågan på byggnadsytor. Delning av ytor kan bidra till att optimera användningen av byggnadsytor inomhus, men flera faktorer begränsar sådana initiativ. Det kräver ändrade rutiner bland byggnadsanvändare och fastighetsförvaltare, såsom nya affärsmodeller och prestandamått som bättre kan synliggöra hur byggnader används. Otydligheter i regelverk och kommunala planer när det gäller hur de hanterar delade och multifunktionella byggnader hindrar också delningsinitiativ (till exempel otydlighet kring rättigheter och ansvar för hyresgäster och fastighetsägare, motsägelsefulla krav på brandsäkerhet eller ventilation, och så vidare). På samma sätt finns det regulatoriska oklarheter kring i vilken utsträckning kommuner, som myndigheter, får ställa krav för att främja låg klimatpåverkan. Miljöprestandakrav på byggprojekt medför också hinder i form av att de kräver mer intern kompetens, tillgång till data, tid och resurser. För att kunna ställa klimatkrav för nybyggnation, krävs att kommuner först löser kompetens- och dataluckor. Liknande hinder visades när det gäller användningen av LCA i offentliga bostadsprojekt. I sådana projekt upprätthåller artefakter, såsom regelverk, detaljplaner och interna krav hos beställarorganisationen, en viss nivå av hållbarhetsarbete samtidigt som de också kan begränsa designmöjligheter. Andra artefakter förenklar designarbetet och skapar standardiserade basalternativ. I sådana fall tas, för miljöprestandan, kritiska designbeslut utanför projektet, det vill säga när dessa kriterier, krav och standardalternativ utvecklas.

Avhandlingen visar också hur kvantitativa miljöbedömningar kan påverka byggprojekt och fastighetsförvaltning, till exempel genom införande av miljöprestandakriterier i regelverk och upphandling. Förutom utmaningar relaterade till kunskap, data, tid och resurser som nämns ovan, understryker avhandlingen variationer i LCA-resultat på grund av val av metod och datakällor. När det gäller klimatpåverkan från underhåll och utbyte av byggnadsmaterial påverkar valet av referensstudieperiod (RSP) den relativa betydelsen av dessa processer, där en längre RSP gynnar produkter med längre livslängder. Livslängsdata skiljer sig mellan olika källor, vilket tyder på ett behov av mer tillförlitliga data. Användningen av ett avrundat eller årligt antal operationer gör dessutom liten skillnad i genomsnitt, men kan leda till tydligt olika resultat i specifika fall. Detta visar på att det finns ett behov av att harmonisera och förfina detaljer i metodval nu när LCA i allt högre grad börjar komma in i upphandling och regelverk för byggnader.

Vidare uppmärksammar avhandlingen också mer komplexa effekter av miljöprestandabedömningar i bostadsprojekt. Populära certifieringssystem kan bli de facto definitioner av hållbarhet för vissa aktörer, och påverkar designval även i projekt som inte är certifierade. Dessutom kan miljöbedömningssystem dölja eller synliggöra vissa aspekter av hållbarhet. Allmänt använda verktyg kan fungera som "svarta lådor", där kriterier för vad det betyder för en byggnad att vara hållbar döljs och inte längre ifrågasätts. Denna process bidrar till att operationalisera hållbarhet i byggprojekt, men kan leda till att viktiga aspekter också ignoreras. Till exempel är konventionella energiprestandamått vanligen normaliserade för golvarea, vilket ignorerar hur ytan används och hur yteffektiv byggnaden är. Å andra sidan kan kvantitativa bedömningar också belysa viktiga aspekter av den mångfacetterade hållbarhetsfrågan. Avhandlingen exemplifierar detta genom kvantitativ modellering av backcasting-scenarier för att synliggöra viktiga klimatstrategier, och genom att visa på energimått som tar hänsyn till användning och yteffektivitet.

Nyckelord: byggnad, hållbarhet, miljöprestandabedömning, livscykelanalys, beslutsstöd

Preface

My PhD was carried out in an interdisciplinary research environment, at the department of Sustainable Development, Environmental Science and Engineering (SEED) at KTH Royal Institute of Technology. A red thread throughout my research has been the global warming potential (GWP) of buildings in general, and building life cycle assessment (LCA) in particular.

I started my PhD following a master thesis and a year as a research assistant. I spent this time developing a quantitative model of buildings' GWP in future scenarios, and a survey about measures taken by Swedish municipalities to promote low-GWP construction. I came from an engineering background and approached these projects as engineering problems, focusing on where to find accurate data and how to develop and implement my model. However, I kept reflecting on the accuracy of the model and the arbitrary choices I made while developing it. What were the value and meaning of this work? It was a quantitative exercise, but it was clearly different from what I had previously encountered in engineering, since its value did not lie in its accuracy or predictive power, but rather in how it supports a discussion of buildings' characteristics in various future scenarios.

Later, LCA became a key theme of many of my projects. I realized that building LCA results are sensitive to choices of method and data source, and yet there is value and interest in using LCA in decision making. Both of these experiences led me to want to understand more about the value and meaning of quantifying environmental performance for decision support. Accordingly, my thesis combines quantitative studies about assessing environmental performance and qualitative studies about what actually happens when such assessments are used, e.g. in housing projects, space sharing projects and municipal policies. More broadly, I tried to identify challenges to the implementation of particular measures that could help mitigate buildings' GWP.

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It has been a privilege to spend these years at KTH, to do research, to teach and (most importantly) to keep learning myself. I am grateful to Energimyndigheten, Formas, SBUF and Boverket for funding my various projects and giving me the opportunity to do this PhD.

I wouldn't be where I am, know what I know or do what I do without the invaluable support and input of people around me. I would like to thank my supervisors for guiding me throughout this PhD. I have realized that the success of a PhD depends to a very large extent on the relationship between the PhD student and their supervisors, so I am very grateful that mine were so supportive. Thanks in particular to Tove Malmqvist for offering me to start this PhD and for constantly supporting and advising me ever since. Thanks to Mattias Höjer for both his creative and innovative ideas, and his very pragmatic contributions. Thanks to Martin Erlandsson for his input and for helping me stay connected to what's practically relevant "in the real world".

I would also like to thank my colleagues at KTH SEED for making our department such a stimulating and welcoming environment. Although we haven't interacted much this past year due to the covid-19 pandemic, the SEED spirit lives on, and it's been a pleasure to come back to the office and see you again these past few weeks. Working remotely this last year and a half has made me keenly aware of how important it has been for me to interact with you. So thank you for your creativity, motivation and support, and for sharing lunch or fika with me.

Thanks as well to all coauthors and collaborators who worked with me throughout my thesis, including Pernilla Hagbert, Josefin Florell, Kristina Mjörnell, Allan-Mikel Orahim, Jenny von Platten, Torun Widström, Alice Moncaster, Kyriacos Polycarpou and all other members of the IEA EBC Annex 72 program. Thank you to all stakeholders from public and private organizations who participated in my research through interviews or by providing data.

Finally, thanks to my family, friends and loved ones, whose presence (physical or remote) and support mean more to me than I can express in this short paragraph. To my parents and brothers, thank you for being with me despite the distance (merci d'être là pour moi malgré la distance)! To

Rémi, Taras, Julie and all my friends in Sweden and back in France, thank you for our fulfilling discussions and our moments of plain, simple fun. To Linus, Viktor, Mark and Ida, thank you for the stories we make up. And last but certainly not least, thank you to Emmy. I feel incredibly lucky to have met you, and I am grateful beyond words for your love, "yes-anding", energy, wisdom, and for being with me through sunny days and tough times.

Nicolas Francart

Stockholm, October 2021

List of papers included in the thesis

<u>Paper 1:</u> Francart, N., Malmqvist, T., & Hagbert, P. (2018). Climate target fulfilment in scenarios for a sustainable Swedish built environment beyond growth. *Futures*, *98*, 1–18. https://doi.org/10.1016/j.futures.2017.12.001

<u>Paper 2:</u> Francart, N., Larsson, M., Malmqvist, T., Erlandsson, M., & Florell, J. (2019). Requirements set by Swedish municipalities to promote construction with low climate change impact. *Journal of Cleaner Production*, *208*, 117–131. https://doi.org/10.1016/J.JCLEPRO.2018.10.053

<u>Paper 3:</u> Francart, N., Höjer, M., Mjörnell, K., Orahim, A. S., von Platten, J., & Malmqvist, T. (2020). Sharing indoor space: stakeholders' perspectives and energy metrics. *Buildings and Cities*, *1*(1), 70–85. https://doi.org/10.5334/bc.34

<u>Paper 4:</u> Francart, N., Widström, T., Malmqvist, T. Influence of methodological choices on maintenance and replacement in building LCA (Accepted for publication in *International Journal of LCA*)

<u>Paper 5:</u> Francart, N., Polycarpou, K., Malmqvist, T., Moncaster, A. How artefacts mediate sustainability in public housing projects (Manuscript)

Contributions to each paper

<u>Paper 1:</u> I developed the spreadsheet model and performed the quantitative analysis presented in the paper. The model built on an earlier version developed during my master thesis. The scenarios analyzed were based on qualitative descriptions developed by other researchers. I was the main author of Paper 1 and wrote most of the text. Other coauthors provided comments on the text and the model scope, and helped with writing the introduction, discussion and conclusion and revising the manuscript.

<u>Paper 2:</u> I was responsible for developing and distributing the survey used in Paper 2, as well as carrying out the statistical analysis of the results. I also co- developed the interview template. The interviews were carried out by Mathias Larsson and Josefin Florell. Mathias Larsson passed away during the project, and Josefin Florell was not involved in writing the article. Therefore, I worked with exploiting the interview results based on transcripts, and wrote most of the text in Paper 2. Other co-authors were responsible for problem formulation and initial study design, and provided comments and revisions on the paper.

Paper 3: I was responsible for carrying out and analyzing the interviews presented in Paper 3. I participated in the workshop and analyzed its outcomes, but I was not responsible for organizing it. I carried out the review of energy performance metrics together with Jenny von Platten. I wrote most of the text in Paper 3. Other co-authors contributed with initial problem formulation, text suggestions, comments and revisions.

Paper 4: I contributed to gathering environmental data and material inventories, as well as implementing LCA calculations in a spreadsheet. I was the main responsible for calculations of carbon uptake through carbonation, as well as scenario analyses using different reference study periods, service life values and calculation methods for maintenance and replacement. I wrote all the text in Paper 4. Other co-authors also contributed to data gathering and model development, and provided comments and feedback on the article.

Paper 5: This study was carried out in close collaboration with Kyriacos Polycarpou. We co-designed the interview template together. He carried out interviews in Cyprus while I carried out interviews in Sweden. We both analysed our own transcripts first, and then read the other's transcripts. I was the main responsible for writing Paper 5, but Kyriacos Polycarpou also contributed to the writing. Other co-authors contributed with initial problem formulation and study design, as well as comments, feedback and revisions on the article.

Peer-reviewed publications not included in the thesis

Frischknecht, R., Ramseier, L., Yang, W., Birgisdottir, H., Chae, C. U., Lützkendorf, T., … Zara, O. (2020). Comparison of the greenhouse gas emissions of a high-rise residential building assessed with different national LCA approaches – IEA EBC Annex 72. *IOP Conference Series: Earth and Environmental Science*, *588*, 022029. https://doi.org/10.1088/1755-1315/588/2/022029

Frischknecht, R., Birgisdottir, H., Chae, C.-U., Lützkendorf, T., Passer, A., Alsema, E., … Yang, W. (2019). Comparison of the environmental assessment of an identical office building with national methods. *IOP Conference Series: Earth and Environmental Science*, *323*(1), 012037. https://doi.org/10.1088/1755-1315/323/1/012037

Francart, N., & Malmqvist, T. (2020). Investigation of maintenance and replacement of materials in building LCA. *IOP Conference Series: Earth and Environmental Science*, *588*, 032027. https://doi.org/10.1088/1755-1315/588/3/032027

Francart, N., Sandberg, E., & Erlandsson, M. (2019). Environmental Sustainability Building Criteria for an Open Classification System. In J. D., B. H., & W. Å. (Eds.), *Cold Climate HVAC 2018*. Springer Proceedings in Energy. Cham. https://doi.org/10.1007/978-3-030-00662-4_85

List of abbreviations

LCA: Life cycle assessment

RSP: Reference study period

GHG: Greenhouse gas

GWP: Global warming potential

ANT: Actor-network theory

CCS: Carbon capture and storage

Note on terminology

Throughout the thesis, the terms “greenhouse gas (GHG) emissions” and “global warming potential (GWP)” will be used when the issue at stake is exclusively climate change. Technically, the term “GHG emissions” refers to the amounts of various GHG released in the atmosphere, while “GWP” refers to the impact that these emissions have on the climate, usually expressed in kg CO2-equivalent. However, in many situations, the two terms are used interchangeably. “GHG emissions”, “low-carbon” or “climate impact” are more commonly used in e.g. policymaking and “GWP” is commonly used in life-cycle assessment.

The terms “environmental impacts” and “environmental sustainability” will be used when several impact categories could be concerned. The term “sustainability” will be used when social aspects could be relevant as well.

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1 Introduction

1.1 Fulfilling climate targets in the building sector

Challenges related to environmental sustainability have become increasingly urgent to address at the global level, as their consequences are already visible and often worsening (Steffen et al., 2015). Among these, climate change is certainly the most debated issue, especially following alarming reports from the Intergovernmental Panel on Climate Change (IPCC, 2021). Accordingly, targets, roadmaps and strategies are being developed at a global, national and local level. When it comes to climate change, the most recent global target that is largely agreed upon is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels", as stated in the Paris agreement (United Nations Framework Convention on Climate Change, 2015). This global target provides a focal point to communicate, coordinate and negotiate actions to stabilize global average temperature (Jaeger & Jaeger, 2011).

Various roadmaps, greenhouse gas (GHG) emission targets and budgets have been developed to translate this global target at smaller levels. At the level of the European Union (EU), the "Roadmap for moving to a competitive low carbon economy in 2050" aims for a reduction of GHG emissions by 80-95% in 2050 compared to 1990 levels (European Commission, 2011). At a national level, focusing on the case of Sweden, a climate policy framework has been developed, with targets to reduce GHG emissions by 63% by 2030 (compared to 1990 levels), 75% by 2040 and to net zero emissions by 2045 (Government Offices of Sweden, 2018). Part of this reduction is meant to be achieved through the use of carbon capture and storage (CCS) technologies.

The building sector is a major contributor to issues such as climate change and resource depletion. Various estimates attribute about a third of global final energy use and between a fifth and a third of GHG emissions to the building sector (International Energy Agency, 2013; Lucon et al., 2014). Buildings require large amounts of materials, as well as heat and electricity during their operation. In a context of ever-expanding urbanization, it is therefore urgent to change practices in the building sector in order to reach climate targets and other sustainability targets.

In Sweden, specific roadmaps have been developed to enable a low-carbon transition for various economic sectors within the initiative "Fossil-free Sweden", which gathers actors from various organizations within the public and private sectors. For the building sector, recommendations include, among others, the introduction of ambitious and predictable long-term requirements and declarations of global warming potential (GWP), based on a life-cycle perspective. Suggested policy instruments include regulatory changes, subsidies, public procurement and the provision of tools and data to assess GWP, while private sector actors are encouraged to report emissions as well as set and follow requirements based on life cycle GWP (Fossil-free Sweden, 2018). Accordingly, a mandatory declaration of GWP from the production and transport of construction materials as well as processes on the construction site for all new construction projects will be introduced in January 2022 (Swedish Parliament, 2021). The Swedish National Board of Building, Housing and Planning has also proposed to introduce other life cycle stages and limit values in 2027 (Swedish National Board of Housing Building and Planning, 2020). In the private sector, there are also initiatives to promote emissions reporting and a commitment to internal "science-based" emissions targets in line with the Paris Agreement (Science-Based Targets, 2021). Finally, some local public authorities have taken up a proactive role and established local climate targets, carbon budgets or specific roadmaps for the building sector. This is for instance the case of Östergötland County (Östergötland County Administrative Board, 2021) and the City of Malmö (Holmgren & Erlandsson, 2021).

Reaching such ambitious sustainability targets requires a far-reaching transition, addressing many different aspects of how buildings are constructed and operated (Hagbert et al., 2019). Addressing the multifaceted issue of sustainability requires a future strategy that breaks with current unsustainable trends, policy instruments that steer towards more sustainable practices, and appropriate decision support tools to guide decisions today.

Much attention has been dedicated to incremental improvements in environmental performance and technological solutions. Initiatives exist to improve the energy performance of buildings, such as the EU "Renovation wave" initiative, which aims to double the annual rate of building energy renovation in the EU and foster deep energy renovations (European Commission, 2020). There are also scenarios and roadmaps for the decarbonisation of the construction industry, aiming to achieve ambitious climate targets through technological changes in material production, such as the use of slag or fly ash in cement, electrification of kilns, or carbon capture and storage (CCS) (Favier, De Wolf, Scrivener, & Habert, 2018; I. Karlsson et al., 2020). Some of these prevalent technological solutions are dependent on the possibility of producing large amounts of electricity with low GHG emissions, and of scaling up CCS. While such improvements are important, it is relevant to also address issues and strategies that are less discussed. More in-depth changes to prevalent paradigms have the potential to leverage change when current trends are unsustainable (Abson et al., 2017; Meadows, 1999). Therefore, there is a need to reconsider images of the future regarding how buildings are and will be designed, constructed and operated. Future scenarios can inform a discussion of what issues and strategies to priorities in order to reach sustainability targets and support policymaking (van Dorsser, Walker, Taneja, & Marchau, 2018). A challenge is then to translate these images of the future into more concrete changes in practices at the level of building projects and organizations.

At a more operational level, appropriate measures must be implemented to enable sustainable practices. For policymakers and public authorities, this can entail implementing appropriate incentives and requirements. For private sector actors, this can entail changes in technology, business models, routines and the adoption of appropriate decision support and design tools. Accordingly, it is necessary to understand and overcome challenges to these practices, and the "implementation gap" between actors' stated ambitions and measures that are actually implemented (M. Karlsson & Gilek, 2020).

A wider use of environmental performance assessment tools could potentially support design- or investment decisions and enable the implementation of environmental criteria in e.g. procurement. Life-cycle assessment (LCA) has long been used to assess the environmental impact of buildings or building elements (Buyle, Braet, & Audenaert, 2013). It is already widely used within academia and in voluntary certification systems such as LEED and BREEAM. It is now starting to be used in procurement and regulation in several countries. LCA can help inform decision makers at various levels about what practices are likely to lead to lower environmental impacts, and decision makers can drive the adoption of LCA by requiring its use e.g. in procurement, certification or regulation. Since Sweden is introducing a mandatory LCA-based declaration of GWP for new building projects in 2022, now is a particularly important time to study the roles that such environmental performance assessment tools can play in decision support, and possible challenges to their implementation (Swedish National Board of Housing Building and Planning, 2020).

1.2 Aim of the thesis

Overall, this thesis addresses decision support to construct and operate buildings in accordance with fulfilling ambitious climate targets such as the Paris Agreement. In particular, the thesis explores challenges to the implementation of GWP mitigation strategies that have received only little attention so far, such as efficient use of indoor space and mitigation of embodied GWP in construction materials. It also emphasizes the practical role of quantitative assessments of environmental performance such as LCA as decision support tools. The following research questions are addressed:

RQ1: What challenges hinder practitioners from implementing measures to mitigate life cycle GWP and resource use in the construction and operation of buildings?

RQ2: In what ways could quantitative assessments of environmental performance provide decision support to steer towards low environmental impacts in the building sector?

Although some findings of this thesis can also apply to other environmental impact categories, the focus throughout the thesis is primarily on the mitigation of GWP, as it is currently the most discussed environmental issue among policymakers and practitioners. However, Paper 3 also focuses on operational energy use, and Paper 5 addresses "environmental performance" as defined by the interviewees themselves.

The thesis addresses the perspectives of several relevant practitioner groups in the building sector. Public authorities are considered as key actors since they have the power to set the rules that must be followed by market actors. While the importance of public authorities at a national level is acknowledged, the thesis addresses the less studied role of local public authorities such as municipalities. The perspectives of industry practitioners are also considered, notably developers, building designers and material producers. These actors play an essential role in implementing environmental sustainability strategies in the building sector and are a key target for decision support tools such as LCA. Finally, the thesis briefly addresses the perspective of building users regarding efficient use of indoor space and space sharing initiatives. Table 1 specifies how each paper in the thesis addresses questions related to different facets of RQ1 and RQ2.

Table 1 – Relation of the various papers to each research question of the thesis. Practitioners whose perspective is addressed are mentioned in bold.

<table>
<tr><th></th><th>Relation to RQ1</th><th>Relation to RQ2</th></tr>
<tr><td>Paper 1</td><td>Identifies strategies that should be considered for mitigating GWP in the building sector.
Identifies possible conflicts and trade-offs between different strategies.</td><td>Exemplifies how a quantitative model of buildings’ GWP can support a discussion of GWP mitigation strategies.</td></tr>
<tr><td>Paper 2</td><td>Identifies challenges to the use of requirements by Swedish municipalities to promote construction with a low climate change impact.</td><td>Discusses the difference between requirements based on a quantitative assessment of environmental performance and prescriptive requirements.</td></tr>
<tr><td>Paper 3</td><td>Explores key aspects of space sharing initiatives that differ from conventional use of space, from the perspectives of building users.
Identifies challenges that limit the implementation of space sharing from the perspectives of building designers and real-estate managers.</td><td>Reviews complementary energy performance metrics that could incentivize higher occupancy and efficient use of space.</td></tr>
<tr><td>Paper 4</td><td colspan="2">Assesses to what extent methodological choices related to the assessment of maintenance and replacement processes in LCA can influence LCA results.
Assesses uncertainties caused by the difference between service life data from material producers and generic data from the literature.</td></tr>
</table>

	Relation to RQ1	Relation to RQ2
Paper 5	Identifies how artefacts mediate, enable or hinder sustainability considerations in the work of **designers, contractors and project managers in housing projects**.	Discusses the effects of environmental performance assessment tools in real decision situations.

1.3 Structure of the thesis

Section 2 provides a theoretical background and describes the research context of the thesis. Section 3 details the methods used in the various papers of this thesis in relation to the two research questions. Section 4 presents the results of the research in relation to the two research questions. Section 5 discusses and elaborates on the outcomes of the research work. Section 6 provides a conclusion emphasizing the main takeaways of the thesis. The appended papers are briefly summarized below, and the links between these papers are illustrated in Figure 1:

Paper 1 presents a model of buildings' GWP in four future scenarios fulfilling ambitious climate targets. The model supports a discussion of relevant GWP mitigation strategies in the building sector, and of building properties in each of the scenarios.

Paper 2 is a survey- and interview-based study of the extent to which Swedish municipalities set requirements to promote construction with a low GWP. It focuses particularly on challenges to the use of environmental performance requirements.

Paper 3 is an exploratory study of key characteristics of space sharing initiatives (coliving and coworking) and challenges to their implementation. It is based on interviews with building users and practitioners, a workshop and a literature review of energy metrics that take into account occupancy and space efficiency.

Paper 4 is a comparative LCA of seven alternatives for the façade of a building. It investigates to what extent choices of reference study period, service life data and calculation method influences the calculated GWP.

Paper 5 examines how various artefacts mediate actors' work with sustainable design in housing projects. It is based on qualitative case studies of public housing projects in Sweden and Cyprus.

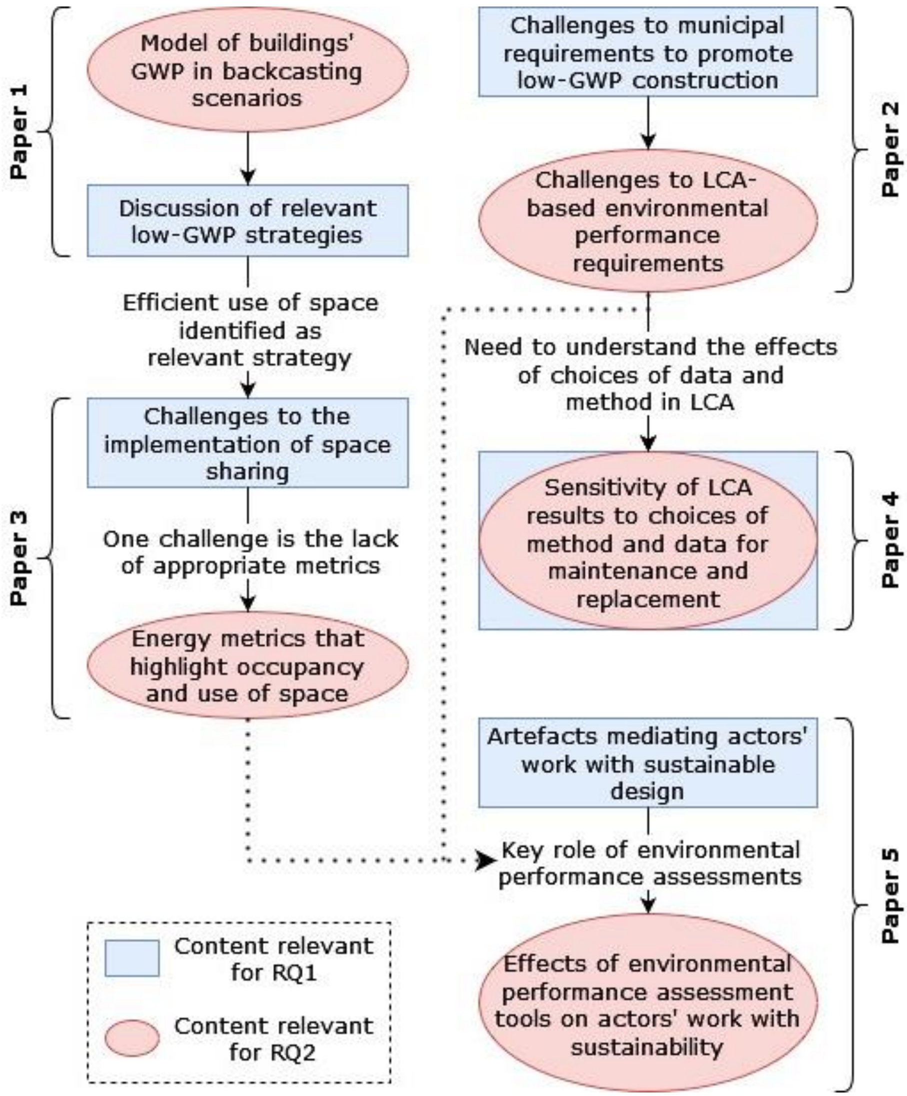


Figure 1 - Logical structure of the thesis and the appended papers

2 Research context

2.1 Grounding within sustainability science

This thesis is situated within the field of sustainability science. Sustainability science emerged as a research field around the turn of the millennium, from a growing need for research practices that could understand and help address global sustainability issues (Clark & Dickson, 2003; Kates, 2001; Komiyama & Takeuchi, 2006). Sustainability science as an academic field is unique in several regards. Since it is geared towards tackling particular societal issues, it is inherently problem-driven and focuses on knowledge that can support decision making towards sustainability transitions. This knowledge comes in the form of both critical and problem-solving approaches and covers understanding sustainability issues, setting appropriate sustainability targets and elaborating pathways to reach these targets (Jerneck et al., 2011).

To define further the type of knowledge produced within sustainability science, it is useful to distinguish between multidisciplinary, interdisciplinary and transdisciplinary approaches. Multidisciplinary research involves researchers from several disciplines working on the same object of study, but only in parallel, with limited interaction. On the other hand, interdisciplinary research involves the combination and integration of knowledge from multiple disciplines in close interaction, to provide a holistic understanding beyond the mere combination of distinct results. Finally, transdisciplinary research challenges traditional views of knowledge production as a monopoly of academia. It involves extended communities from the rest of society in the definition of research questions, the production of knowledge, and its dissemination (Komiyama & Takeuchi, 2006; Lang et al., 2012; Spangenberg, 2011). Since sustainability issues stem from complex interactions between socio-ecological systems, sustainability science must deal with uncertainty and complexity and combine insights from different disciplines. Therefore, knowledge in sustainability science integrates approaches from both social and natural sciences and is often produced through a cooperation between academia, industry and/or civil society. In that regard, sustainability science is often conceptualized as requiring inter- or transdisciplinary perspectives.

Spangenberg (2011) distinguishes between two branches of sustainability science: science for sustainability and science of sustainability. The former is primarily multi- and interdisciplinary. It is characterized by a focus on problem solving and identifying appropriate solutions to sustainability issues, to be implemented by other decisions makers. It does not aim to challenge existing institutions. On the other hand, science of sustainability focuses on the specificity and complexity of sustainability itself. It aims at understanding the underlying mechanisms of sustainability issues and interactions between socio-ecological systems. As such, it is critical of societal institutions and the role of science itself, and relies more on transdisciplinary forms of research.

For the most part, the present thesis comprises interdisciplinary science for sustainability. It is an attempt at addressing the complex issue of extensive mitigation of GWP within the building sector. One starting assumption is that this issue is multifaceted and cannot be solved with solutions that are rooted in a single perspective, e.g. only technical solutions or only policy measures. The thesis embraces the idea that analyzing an issue from multiple perspectives can grant a rich understanding of problems and potential solutions. Accordingly, the thesis is not grounded in a single paradigm, but relies on both quantitative and qualitative inquiries, and insights from both natural and social sciences. The focus is primarily on identifying practical issues for the implementation of GWP mitigation strategies, although Paper 1 also supports a more critical perspective by discussing radical alternative future scenarios. Most papers in the present thesis integrate the perspectives of stakeholders and building sector practitioners, but there is no co-production of knowledge *per se* as the research is still conducted by the researchers.

2.2 Futures studies

Futures studies are a broad range of methods and approaches to investigate possible, probable or preferable futures. In other words, the field investigates questions regarding what the future could be, what it is likely to be, and what it should be (Bell, 2003). Western futures studies in the mid- to late 20th century focused primarily on positivist forecasting of technological, economic or military scenarios, and later on business management (Son, 2015). Towards the end of the 20th century, global sustainability became a major focus of futures studies, with the notable publication of The Limits to Growth, a report including scenarios on global-scale economic and environmental issues (Meadows, Meadows, Randers, & Behrens, 1972). Besides strategic foresight focused on mathematical modeling of trends for business and policymaking, more critical, less deterministic approaches based on qualitative and participatory methods arose, exploring alternative futures and questioning existing trends and paradigms (Schultz, 2015; Son, 2015). Modern futures studies are therefore characterized by a multiplicity of goals, methods and ways of knowing (Bengston, Kubik, & Bishop, 2012; Curry & Schultz, 2009). Börjeson, Höjer, Dreborg, Ekvall, & Finnveden (2006) distinguish between:

- Predictive studies (predicting likely futures based on present trends or on hypothetical outcomes of important events)

- Explorative studies (considering possible futures taking into account changes of external factors or internal decisions), and

- Normative studies (imagining desirable futures focused on fulfilling a long-term target by either preserving or transforming current paradigms).

In Paper 1, a quantitative model is used to support a discussion of future GWP mitigation strategies in the building sector that are consistent with fulfilling a 1.5℃ climate target, and of potential conflicts and trade-offs between different strategies. This study focuses on the fulfillment of a long-term target; it is therefore normative. Moreover, the study starts from the assumption that incremental changes are insufficient to reach the target, and that there is a need to depart from existing trends; it is therefore a transforming study (Börjeson et al., 2006). More specifically, Paper 1 is part of a broader backcasting research program called Beyond GDP Growth (Hagbert et al., 2019). Backcasting is a normative approach to scenario development that starts from an end-point where specific conditions are fulfilled, and works backwards to consider different ways in which this end-point could be reached. It is particularly appropriate to address complex problems over long time horizons, requiring major changes and a departure from current trends and paradigms. It can be used to spark ideas, broaden perspectives and envision solutions that could appear unfeasible in light of current trends (Dreborg, 1996; Vergragt & Quist, 2011).

Previous studies have used qualitative and participatory approaches to develop backcasting scenarios e.g. for energy use in buildings or the building sector as a whole (Doyle & Davies, 2013; Svenfelt, Engstrom, & Svane, 2011) and for the use of wood construction products (Hurmekoski, Pykäläinen, & Hetemäki, 2018). However, quantitative modelling can be used to complement backcasting scenarios and elaborate on specific aspects of a scenario. For instance, Pereverza, Pasichnyi, & Kordas (2019) proposed a framework for modular participatory backcasting where quantitative and qualitative methods inform each other at various steps of the process. Previous studies have used quantitative modelling of GWP in backcasting, focusing e.g. on modelling macro level input-output flows (Fujino et al., 2008) or the application of specific policy measures (Gomi, Ochi, & Matsuoka, 2011).

Paper 1 has a different purpose and approach, and uses a quantitative modelling of GWP in the building sector in order to illustrate how buildings could be designed and operated in four radically different backcasting scenarios. The aim is to link directly micro-level building properties (e.g. size, energy performance, materials) to indicators for the building sector (e.g. energy use, GWP). In addition, Paper 1 addresses the need to quantify whether reaching climate targets would lead to high levels of operational energy use and/or cumulative GWP before the year 2050. Another particularity of the study is that the Beyond GDP Growth scenarios are particularly ambitious. They are meant to fulfill far-reaching sustainability targets (e.g. a 92% reduction of GWP from Swedish consumption) and entail radical departures from current paradigms. While numerous countries, municipalities and organizations now have objectives of climate neutrality, one particularity of the Beyond GDP Growth scenarios that makes them stand out as radical is the fact that they do not rely on carbon capture and storage (CCS) as a source of "negative emissions". The reasons behind this limitation are that the potential to scale up CCS was considered uncertain and with limited public acceptance, and that Sweden's environmental objectives at the time did not mention CCS (although the current Swedish Climate Policy Framework does rely on CCS to achieve part of the improvement). Moreover, economic growth is not taken for granted in any of the scenarios. Previous studies that used quantitative modeling in backcasting have been based on less radical scenarios and less far-reaching targets (e.g. a 45% reduction in GWP in Gomi, Ochi, & Matsuoka (2011)).

2.3 Building life cycle assessment (LCA)

The second research question in this thesis considers the role of quantitative assessments of environmental performance for decision support, such as LCA. Throughout the thesis, there is a particular focus on the role of building LCA. LCA is a method for assessing environmental occurring throughout the life cycle of a product or service, from acquisition of natural resources through production and use to disposal and waste management. An LCA study usually comprises four phases (Finnveden & Potting, 2014; International Organization for Standardization, 2006):

1. An initial phase defining the goal of the study and the scope of the system to be assessed. In LCA, impacts are calculated in relation to a functional unit, which quantifies functions fulfilled by the system. A common functional unit for building LCA is for instance "1m^2 of office space to be used during 50 years". The initial phase also includes a selection of impact categories for the assessment (the most common being climate change impact).

2. An inventory phase (LCI) compiling all environmental inputs to and outputs from the system for each phase in its life cycle.

3. An impact assessment phase (LCIA) where materials and energy flows are linked to different impact categories.

4. An interpretation phase where results are evaluated to draw conclusions and recommendations.

LCA applied to buildings was first used in the 1980s. A standardized methodological framework for LCA was introduced in the 1990s, with the ISO 14040 standard. Since then, more building LCA methods and standards have been developed, and there has been a growing interest in building LCA in both research and practice (Buyle et al., 2013). In particular, LCA has been used in voluntary environmental certification (Anand & Amor, 2017). Certification schemes such as LEED and BREEAM grant extra credits for carrying out an LCA. The DGNB system in Germany and Denmark awards points for carrying out an LCA in early planning phases, comparing alternatives with LCA and reaching climate neutrality in the construction and/or operation stages (German Sustainable Building Council, 2018). In Sweden, the Miljöbyggnad system has a criterion requiring a partial LCA of the building frame (limited to the product stage and transport of materials) (Sweden Green Building Council, 2020a). The recent NollCO_2 system for net zero emission buildings in Sweden is also based on a life cycle perspective (Sweden Green Building Council, 2020b).

More recently, LCA is starting to be used in regulation and procurement, to set targets and limit values for new buildings. In particular, from 2022 in Sweden, a declaration of GWP will become mandatory for all new buildings. At first, the declaration will only encompass GWP from the product stage of the building's life cycle, transport and on-site processes (module A in the EN 15978 nomenclature, see Table 2) and will not enforce mandatory limit values or changes in building design. However, the declaration might be later expanded to cover the full building life cycle and to introduce limit values (Swedish National Board of Housing Building and Planning, 2020). Similar initiatives can be seen in other countries, for instance France and Finland (Finnish Ministry of the Environment, 2019; French Ministry for the Ecological Transition & French Ministry for Territorial Cohesion, 2017). Although LCAs in academia have encompassed many different impact categories, these recent regulatory initiatives have primarily focused on GWP.

Table 2 - Modules in a building's life cycle according to the EN 15978 nomenclature

Product stage			Construction stage		Use stage							End of life stage				Benefits beyond the life cycle
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials supply	Raw materials transport	Manufacturing	Transport to site	On-site processes	Use	Maintenance	Repairs	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction-demolition	Waste transport	Waste processing	Disposal	Reuse, recycling, recovery, etc. (reported separately)

As LCA is being increasingly used in practice and LCA outcomes have the potential to influence building design, it becomes crucial to investigate the precision and accuracy of LCA results and recommendations, and ensure that the use of LCA actually steers towards a reduction of environmental impacts. Recent comparative case studies have shown that different LCA methods and data sources are used in different countries, and can yield significantly different results when assessing the same building (Frischknecht et al., 2019, 2020). These discrepancies can be partly explained by differences in choices of parameters (material amounts in the life cycle inventory and environmental data in the impact assessment), scenarios (e.g. for future energy supply and waste handling at the end of life) and calculation model (assumptions, simplifications and methodological choices) (Huijbregts, Gilijamse, Ragas, & Reijnders, 2003; Nygaard Rasmussen, Malmqvist, Moncaster, Houlihan Wiberg, & Birgisdóttir, 2018). Specifically, LCA applied to buildings entails a number of methodological issues and sources of complexity, including the following aspects (Anand & Amor, 2017; Buyle et al., 2013; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Pannier, 2017):

- Different assessments are carried out using different functional units, which hinders comparison. Results are often normalized per unit floor area, but different definitions of floor area are used (e.g. heated floor area, gross floor area, etc.) Moreover, the reference study period (RSP) differs between assessments. In most European countries, it is common to use a 50 or 60 years RSP, but some assessments use longer RSPs. This affects the relative influence of the product and use stages on the results.

- Since buildings have a very long lifespan, it is necessary to make assumptions regarding future scenarios for energy supply, maintenance, replacement and disposal. In other words, the heat and electricity supply of the building might change during its lifespan, the service lives of building components is uncertain, new components installed during replacement operations might be produced with different technologies, and future waste disposal processes might not be the same as current ones.

- Building LCA requires managing large amounts of data, including material amounts for the life cycle inventory and environmental data for the impact assessment. These data can be missing or values may be reported differently in different sources. For instance, identical materials might have different environmental impacts in different databases.

- LCA calculation methods are not fully standardized and differ between assessment systems. For instance, there are differences between studies regarding how to account for the benefits of recycling in the product and/or end of life stages (Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020), the number and types of maintenance and replacement processes, or the timing of emissions, in particular for biogenic carbon uptake and carbonation in cement-containing materials (Collinge, Rickenbacker, Landis, Thiel, & Bilec, 2018).

Therefore, the use of LCA for decision support in practice requires addressing various sources of uncertainty and harmonizing practices. LCA results used as a basis for regulation, procurement and certification should not vary widely based on arbitrary choices made by the LCA practitioner. Initiatives exist to standardize LCA practices. In Europe, the norms EN 15804 and EN 15978 regulate life cycle assessments of construction products and buildings, respectively, although they leave a number of methodological choices open. In addition, a common framework of building sustainability indicators called Level(s) was introduced by the EU Joint Research Center, based on a standardized LCA approach (Dodd, Donatello, & Cordella, 2021).

Operational energy use has often been cited as the main contributor to GWP in building LCA. However, as building energy performance improves and the energy supply becomes less carbon-intensive, the relative contribution of GWP embodied in construction materials increases comparatively to the impact of operational energy use (Anand & Amor, 2017; Blengini & Di Carlo, 2010; Buyle et al., 2013; Chastas, Theodosiou, Kontoleon, & Bikas, 2018; Wallhagen, Glaumann, & Malmqvist, 2011). While impacts from operational energy use and from the product stage have been the focus of a large number of studies, there is also a need to investigate methodological choices in other life cycle stages, and how these would affect the outcomes and recommendations of the assessment. In this thesis, the sensitivity of LCA outcomes and recommendations to methodological choices is addressed in Paper 4, focusing on maintenance and replacement processes for façade materials.

Moreover, from a qualitative point of view, the role of LCA as a decision support tool is addressed in two ways. Paper 2 considers challenges to the use of requirements by municipalities to promote construction with a low GWP, with a particular focus on LCA-based environmental performance requirements. Paper 5 also investigates the potential to integrate LCA in decision processes in housing projects.

2.4 Decision theory and the influence of artefacts on decisions

Understanding challenges to the adoption of measures to mitigate environmental impacts, as well as the role of quantitative assessments of environmental performance, requires a qualitative understanding of the social dynamics at play in real decision processes.

Multiple schools of thought have analyzed decision making. For instance, rational decision making considers that decision-makers try to maximize their expected utility, sometimes accounting for e.g. uncertainties, risk aversion and different definitions of utility (Hansson, 2005). Bounded rationality considers that decision makers are intently rational, but limited by e.g. their attention, memory, comprehension and the context of the decision. Such approaches emphasize biases, simplifications, heuristics and search processes (e.g. choosing the first "good enough" alternative encountered) (March, 1994). Institutional theory considers that decision makers do not follow a rational optimization logic, but rather a logic of appropriateness: they implicitly identify what the situation is, what role they should fulfil in this situation, and what actions are called for (e.g. is the architect acting as an artist, an entrepreneur, a woman, etc.). Some decision situations can be seen as "garbage can processes": somewhat coincidental linkages between decision makers, problems and solutions that happen to be present when the decision is taken (March, 1994). Brunsson (2007) considers that the purpose of many decision processes is not primarily to make a choice, but to mobilize action, create commitment or meaning, or attribute legitimacy to an already-chosen alternative and responsibility to the decision maker. These various theories draw attention to multiple ways of understanding decisions related to e.g. building design or physical planning as being not entirely about rational choices.

The present thesis includes several studies investigating decisions related to the implementation of measures to mitigate environmental impacts, and the potential role of environmental performance assessments. Paper 2 investigates the implementation of requirements by municipalities to promote construction with a low GWP, and Paper 3 investigates space sharing initiatives from the perspectives of building users and practitioners, respectively. In these papers, the level of detail does not allow for an in-depth examination of decision processes. On the other hand, Paper 5 investigates design decisions in housing projects at a higher level of detail, focusing on factors influencing actors' work with sustainable design. In particular, it shows how various artefacts (e.g. documents, tools, etc.) influence decisions related to sustainable design.

The influence of artefacts on decisions has been addressed by scholars from several schools of thought. Social practice theory considers artefacts and their interactions with human agents as essential in enabling persistent routines and patterns of behavior (Shove, Pantzar, & Watson, 2012). Actor-network theory (ANT) treats artefacts as having agency just like human actors, and consider that they play an essential role in solidifying social relations (Latour, 2005). In ANT accounts, action is described through a chain of mediators rather than through straightforward cause-and-effect relationships. Mediators are human and non-human actants that convey meaning but transform it along the way by scripting actions, creating or blocking options, overcoming resistances, etc. For instance, if an actor sends an e-mail to another actor, treating the e-mail as a mediator implies that this medium shaped the meaning of the message, creating a significant difference compared to a situation where these actors would communicate through a face to face conversation, via chat, etc. This notion of mediation is used to discuss the role of artefacts in sustainable design decisions in Paper 5. In situations of stability, some actants might fade in the background and no longer visibly influence actions. They are then considered as intermediaries, which carry meaning directly without transforming it (Georg, 2015; Latour, 2005).

Multiple studies have drawn attention to the roles of artefacts in building projects (Pierce Meyer, 2018; Schmidt & Wagner, 2004; Tryggestad, Georg, & Hernes, 2010; Yaneva, 2009). Nicolini, Mengis, & Swan (2012) highlight multiple roles of artefacts in situations of collaboration. Some concepts are of particular importance for the thesis in general and Paper 5 in particular. Importantly, artefacts can act as boundary objects, forming bridges between different actors, allowing them to understand each other at a surface level. Boundary objects provide a shared language, concrete ways for actors to understand each other's perspectives, and a reification around which to construct shared meaning (Nicolini et al., 2012). Rydin (2013) highlights other roles of artefacts in a development project. She shows how detailed policy documents enabled a municipality to govern from a distance. She also exemplifies how assessments (e.g. of energy performance) can create black boxes, i.e. areas where relationships between actants are stable, taken for granted, and their underlying complexity is invisible. When it comes to understanding the role of quantitative assessments, Espeland & Stevens (2008) mention that numbers are essential for cooperation, control and legitimacy in complex systems and allow actors to control entities from a distance. At the same time, they influence what they measure, create new categories and boundaries, make certain aspects visible or invisible, define what is normal, alter power relationships, elicit action by limiting the reliance on individual judgement, etc.

3 Methods

The present thesis uses a combination of qualitative and quantitative research methods in order to address the two research questions. The primary research methods used have been quantitative modelling of GWP in the building sector, semi-structured interviews, and building LCA. These were complemented in the different studies by a survey, literature reviews, a workshop and document analyses. Table 3 provides an overview of how the various methods were used in the studies presented in the thesis.

Table 3 - Methods used in this thesis and relation to each research question

	Relation to RQ1 *Challenges to the implementation of GWP mitigation measures*	**Relation to RQ2** *Roles of environmental performance assessments for decision support*
Literature review		Paper 3: Review of energy performance metrics considering occupancy.
Modelling of GWP in the building sector	Paper 1: Spreadsheet model combined with backcasting scenarios to identify issues of interest.	Paper 1: Discussion of how quantitative modelling can support a discussion of GWP mitigation strategies.
LCA	Paper 4: LCA of façade materials focusing on GWP. Sensitivity of LCA outcomes to service life data and methodological choices related to maintenance and replacement.	

	Relation to RQ1 *Challenges to the implementation of GWP mitigation measures*	**Relation to RQ2** *Roles of environmental performance assessments for decision support*
Semi-structured interviews	Paper 2: Interviews with representatives from municipalities to investigate challenges to the use of requirements to promote low-GWP construction. Paper 3: Interviews with architects, managers and users of shared spaces to identify success factors and challenges for space sharing. Paper 5: Interviews with practitioners in public housing projects to identify what mediates, enables and constrains sustainable design choices.	Paper 2: Interviews with representatives from municipalities focusing on LCA-based environmental performance requirements. Paper 5: Interviews with practitioners in public housing projects to investigate the influence of various assessment tools, and identify potential uses of LCA tools for decision support.
Survey	Paper 2: Survey of municipalities' practices related to the use of requirements to promote low-GWP construction.	
Workshop	Paper 3: Workshop with practitioners about challenges to space sharing.	
Document analysis	Paper 5: Analysis of internal documents used in public housing companies.	

3.1 Literature review

Scientific literature, and in some cases grey literature, was reviewed throughout the thesis. An interplay between literature review and empirical work took place. Literature was reviewed at the beginning of research projects to identify research gaps or inform the design of the study and the choice of parameters. Literature was also reviewed after empirical material had been gathered and throughout the analysis. Results from empirical studies highlighted new topics of interest to review, and learnings from the literature review allowed identifying new perspectives for the analysis and situating the results in a broader scientific context. Overall, literature was reviewed using searches on the Scopus and Web of Science search engines using relevant keywords, and by examining papers citing and cited by highly relevant papers (snowballing approach). Reviews were not necessarily comprehensive or exhaustive.

Besides the general integration of literature review and interplay with empirical work mentioned above, literature review made distinct contributions to various studies in the thesis. When developing a quantitative model of GWP for the building sector in backcasting scenarios (Paper 1), literature was reviewed about key aspects of each scenario, in order to inform the choice of values for various model parameters (e.g. regarding what technologies might be used in each scenario). In the study of how Swedish municipalities set requirements to promote low-GWP construction (Paper 2), literature played an important role in clarifying the legal context and regulatory ambiguities surrounding the use of such requirements. When studying the implementation of space sharing (Paper 3), literature review was used not only to support the research work, but directly as a method of exploratory research. A more structured review provided insights into the use of energy performance metrics that take into account occupancy and space efficiency. When carrying out a comparative LCA study of façade materials (Paper 4), an initial literature review was used to list and explain various methodological reasons for discrepancies in the impacts of maintenance and replacement processes in published studies. Finally, when studying how artefacts mediate sustainability in housing projects (Paper 5), a literature review highlighted various roles of artefacts shown in previous studies. Theoretical concepts developed in previous studies (e.g. "black boxes" and boundary objects) also informed the analysis.

3.2 Quantitative modelling of environmental impacts

Since the thesis addresses how quantitative assessments of environmental performance could steer towards low environmental impacts, part of the research work was dedicated to the use of such assessment tools. On one hand, GWP from buildings was modelled in four backcasting scenarios, to support a discussion of the properties of buildings in each scenario and of important future GWP mitigation strategies (Paper 1). On the other, a comparative LCA case study investigated the sensitivity of LCA results to choices of data source and method, in relation to maintenance and replacement processes (Paper 4).

3.2.1 Quantitative modelling in backcasting as a way of highlighting issues of interest

A quantitative model of buildings' GWP was used together with a backcasting study in order to illustrate building parameters in backcasting scenarios and identify sensitive parameters (Paper 1). This serves two purposes in relation to the research questions. In relation to RQ1, this study highlights issues of interest that deserve consideration, and thereby helps framing the scope of sustainable practices that should be studied further. In relation to RQ2, this study explores to what extent a quantitative assessment of climate impact can support discussions of sustainability strategies in the building sector.

The modelling study took place after the qualitative development of four backcasting scenarios. Each scenario had been previously elaborated to fulfil four sustainability targets in 2050 (equal distribution of power, fair and sufficient access to welfare, GHG emissions from Swedish consumption compatible with keeping global warming under 1.5°C, and land use that does not exceed global biocapacity) without any precondition of economic growth. The four scenarios were the following (Hagbert et al., 2019; Svenfelt et al., 2019):

- Circular economy in the welfare state, focusing on very high material efficiency and closed loops in a centralized service economy,
- Automation for quality of life, focusing on automated technological solutions to operate most processes in an optimal way, as well as a voluntary reduction in consumption and paid work,

- Local self-sufficiency, based on a relocalization of activity in primarily rural communities, with a comparatively lower level of technological solutions and consumption
- Collaborative economy, organized around urban clusters to maximize the sharing of space, goods and services.

In the study presented in Paper 1, quantitative modelling of GWP in the building sector was used to bring a new perspective to the ongoing discussion of these scenarios, in particular regarding the characteristics of buildings and the strategies used to reach the climate target in each scenario. A spreadsheet tool was developed to model GWP in housing and office buildings (including e.g. heating, electricity use, new construction and renovation of buildings). The model was based on a bottom-up approach. Parameters linked to physical properties of the buildings (e.g. floor area, materials, energy performance) were used to calculate separately emissions from construction, operational energy use and renovation. This bottom-up approach allowed to directly link parameters of the model to the design and properties of buildings in each scenario. This allowed an easy dialogue between the spreadsheet model and the qualitative scenario descriptions, the descriptions informing parameters of the model and the model results illustrating properties of buildings in each scenario. The downside of this bottom-up approach is a truncation error: piecing together estimated impacts from different processes leads to some processes being omitted or oversimplified. Therefore, the model cannot be said to provide a comprehensive estimation of GWP in the building sector. The alternative would be to use a top-down approach based on an input-output model of the building sector: this would allow a comprehensive modelling of emissions within the sector, but the parameters would correspond to resource flows within the sector and would be more difficult to link with building properties.

Beside the limitations inherent to the choice of a bottom-up approach, it should be noted that making quantitative assessments in radical backcasting scenarios entails uncertainties and assumptions regarding e.g. future technological development. In a backcasting study, the point of the study is precisely to break from current trends. Contrary to forecasting studies, assumptions on e.g. future levels of energy efficiency or available construction technologies should not be made based on past trends. When working with scenarios that are radically different from the present and from each other, these assumptions were educated guesses based on a review future prospects for e.g. construction materials or electricity production. However, in this kind of backcasting study, the point is not to predict how buildings will look like in the future, but rather to illustrate what it could entail for buildings to reach the target in each scenario and highlight measures that could be impactful, without focusing on whether they would be economically feasible.

The parameters of the model were then adjusted in four different ways, meant to represent each of the four scenarios above, based on the following criteria:

- Each scenario needs to fulfill the climate target of limiting global average temperature increase to 1.5°C with a 50% certainty. This was estimated to correspond to a decrease in per capita GWP of 92% compared to present day values (Fauré, Svenfelt, Finnveden, & Hornborg, 2016). Therefore, the model was first run with parameters representing roughly current buildings, and a target value was set equal to 8% of the resulting GWP, corresponding to 100 kgCO_2e/(person.year).

- The values of the parameters for each scenario should be consistent with scenario descriptions previously developed in Gunnarsson-Östling et al. (2017).

These four sets of parameters, as well as a sensitivity analysis on each parameter, are then used to support a critical discussion of strategies to fulfill climate targets in the building sector. The model's lack of comprehensive scope means that GWP calculated with the model could not be compared with other comprehensive estimations of emissions of the building sector. The analysis was therefore limited to comparing different runs of the model with each other, to guarantee that the compared estimates are based on the same scope and methodology.

3.2.2 Analysis of the sensitivity of building LCA outcomes to methodological choices

The second research question in this thesis considers the potential role of quantitative assessments of environmental performance to steer towards a reduction of buildings' climate impact. In particular, the assessment of environmental performance with LCA is examined in detail. For LCA to provide reliable steering and decision support, assessment results must be accurate and precise. This thesis examines one particular set of methodological issues that can affect the precision and accuracy of LCA results: issues related to maintenance and replacement processes (Paper 4). This study of maintenance and replacement processes in LCA is motivated both by the relevance of this issue for policymaking and industrial practice, and by the existence of a research gap. First, from a practical perspective, LCA is increasingly used in situations where it has the potential to influence building design, such as voluntary certification, green procurement and regulation. In the case of Sweden, a mandatory declaration of GWP limited to the product stage, transportation and on-site processes will be introduced in 2022. The future introduction of other life cycle stages and of limit values is under discussion (Swedish National Board of Housing Building and Planning, 2020). As such, there is an urgent need to assess the sensitivity of LCA results to methodological choices beyond the product stage, to ensure that LCA steers towards appropriate solutions.

Second, from a research perspective, maintenance and replacement processes in LCA remain comparatively understudied compared to the product stage and operational energy use. Existing building LCA studies show very broad variations when it comes to the relative contribution of maintenance and replacement processes. Some studies highlight these processes as important hotspots of environmental impacts (Gomes, Saade, Lima, & Silva, 2018; Goulouti, Padey, Galimshina, Habert, & Lasvaux, 2020; Hoxha, Jusselme, Andersen, & Rey, 2016), while others consider them insignificant (Cuéllar-Franca & Azapagic, 2012; Lavagna et al., 2018). Beside actual differences in the buildings or materials studied or assumptions about future background scenarios, part of this discrepancy can also be explained by methodological differences in the LCA itself.

The study presented in Paper 4 investigates the sensitivity of LCA outcomes to three parameters in the case of façade materials in the Swedish context: the choice of reference study period (RSP), the choice of service life data, and whether the number of maintenance and replacement operations is calculated with a round-up or annualized method. This is investigated through a comparative attributional case study of seven façade alternatives (brick, non-ventilated render, ventilated render with steel or aluminum structure, fiber cement boards, cedar clapboard panels and spruce cover boards). The study was deliberately practice-oriented and used input from industry practitioners. The alternatives chosen are meant to represent common façade solutions for the Swedish market.

For each alternative, GWP is calculated using each possible combination of the following parameters:

- A RSP of 50, 100 or 200 years. 50 years is a common RSP for building LCA, used for instance in the EU Level(s) assessment framework (Dodd et al., 2021). 200 years corresponds to the longest service life of all the façade alternatives studied.

- Material service lives based on industry values or low, standard or high generic values for the Swedish market compiled by Erlandsson & Holm (2015). The "industry values" were obtained by directly asking manufacturers whenever possible, and from technical documentation found on the manufacturer's website otherwise.

- A round-up or annualized number of replacements.

The assessment is otherwise consistent with the EN 15978 norm (European Standards, 2011), and covers the following life cycle stages:

- A1-A3: Production of construction materials.

- A4: Transport of materials to the construction site.

- A5: On-site processes (limited to wastage of materials).

- B1: Impacts from use (here limited to carbonation in cement-containing materials (European Committee for Standardization, 2017, 2019)).

- B2,B4: Maintenance and replacement of materials during the study period.

- C1-C4: End of life, waste treatment and disposal.

3.3 Qualitative inquiry into the implementation of sustainable practices

Several of the studies in this thesis analyze challenges to the practical implementation of low-carbon practices, from the perspectives of important stakeholders. The thesis investigates the perspectives of various actors in relevant decision situations using qualitative approaches, primarily semi-structured interviews in case studies but also document analysis, a workshop and a survey (Papers 2,3,5).

Case study research is appropriate to gain context-dependent, in-depth knowledge on an issue. Flyvbjerg (2006) argues that context-dependent knowledge is necessary to gain expertise in social science. Indeed, the aim is not to prove a general, predictive rule of behavior, but rather to learn and build up a corpus of in-depth analyses. Closeness to the subject and a narrow scope allow the researcher to better describe all relevant details in the case studied. This extensive understanding of particular cases can allow the researcher to identify unexpected “black swans” that are not well explained by broad theories. It also allows for rich accounts and narratives that go beyond simple summaries and embrace diverse perspectives. The present thesis aims at building up knowledge of challenges to sustainable practices in particular contexts, and of potential roles played by quantitative assessments of environmental performance. Therefore, case study research proved particularly relevant.

In order to get the most out of a case study, cases must be carefully selected (Bryman, 2012). One sampling strategy consists in selecting typical cases, which are most representative of common practice. However, Flyvbjerg (2006) argues that such cases are not necessarily the richest in information, as atypical cases may highlight more clearly specific causes behind a phenomenon. Another sampling strategy consist in selecting critical cases, i.e. cases that present an extreme value along a relevant parameter (e.g. a very large organization). Studying critical cases can provide reference points and allow conclusions such as “if this phenomenon happens in a critical case, then it likely happens in most other cases too”. Alternatively, if multiple cases are studied, cases can be selected to maximize variation along a parameter (e.g. very large, medium and very small organizations).

Semi-structured interviews give insight into how the interviewee understands a situation. Before the interview, a template is prepared with themes to cover and suggested questions. During the interview, the exchange is however open to changes in the sequence and nature of questions, and the interviewer attempts to clarify and follow up on interesting answers from the interviewee (Kvale, 2007).

The following sections detail how case studies, interviews and other methods of qualitative inquiry were used in the thesis.

3.3.1 Analysis of barriers and drivers to the sharing of indoor space

As efficient use of space was highlighted as an important neglected GWP mitigation strategy during the backcasting modelling study (Paper 1), an exploratory study further identified key aspects of space sharing and challenges to the implementation of space sharing practices, from the perspectives of building users and practitioners (Paper 3). The scope was deliberately broad and aimed at generating ideas and pinpointing knowledge gaps and topics of interest based on interviews and a workshop with practitioners.

Cases were selected to maximize variation in terms of the types of cases covered and the roles of stakeholders interviewed, thus covering a broad diversity of perspectives in a small number of interviews. Eight semi-structured interviews were carried out with members of a coworking space and two cohousing collectives, as well as architects and managers in companies that design or manage shared spaces. The interviews addressed primarily the identities of leaders and users of each project, organization, communication and conflict resolution within the community, as well as practicalities such as cleaning, logistics, etc.

Additionally, a workshop was organized with building sector practitioners (including engineers and a manager from real-estate companies, architects and a researcher). The participants were divided in two groups. Each group discussed the following two topics: "Reducing the use of space in housing" and "Promoting space efficiency through performance metrics". Members of the research team facilitated and documented these discussions. Notes from the workshop and the interviews were then analyzed together to identify key relevant themes. As the purpose of the study was exploratory, no particular analytical framework was used during data analysis.

3.3.2 Investigation of the possibility for municipalities to set environmental requirements in construction

Another facet of the analysis of challenges to GWP mitigation practices is the perspectives of local public authorities. The roles and responsibilities of local public authorities depend on the country, but they can be relevant actors to drive the adoption of sustainability measures due to their knowledge of the local context and ability to react more quickly than national authorities can. Swedish municipalities in particular have been described as proactive actors in driving climate change mitigation (Fenton, Gustafsson, Ivner, & Palm, 2015; Granberg & Elander, 2007; Wretling, Gunnarsson-Östling, Hörnberg, & Balfors, 2018). The use of requirements by Swedish municipalities to promote the construction of buildings with a low GWP was investigated in Paper 2.

First, an online survey was carried out among clerks in Swedish municipalities. It gathered data on their use of measures to promote the construction of buildings with a low embodied GWP. 88 of the 290 Swedish municipalities (30%) participated in the survey. Guidelines from Sue & Ritter (2012) were considered in the design of the survey. The survey addressed the following aspects:

- Whether responding municipalities have policy documents dedicated to environmental issues in construction,

- Their level of familiarity with the issue of embodied GWP in construction materials,

- In what situations they implement measures to promote building products with low embodied GWP, and in what situations they might implement such measures in the future (e.g. in planning, procurement, etc.),

- What kinds of requirements are used, if any (i.e. prescribing specific technical solutions, requiring a documentation of environmental impacts, or requiring a certain level of environmental performance)

A quantitative analysis was performed to identify any possible link between the municipality's available resources and its propensity to use steering tools to mitigate buildings' GWP. Statistical analysis using the Kruskal-

Wallis test and the Dunn test were used to determine whether the results depend on the municipality's population, used as a proxy for its size and resources (Dunn, 1964; Kruskal & Wallis, 1952). The survey also served a more exploratory, qualitative purpose: it allowed identifying particularly interesting answers hinting at aspects that deserve further examination.

Follow-up interviews were then carried out in order to investigate in more detail key aspects identified in the survey and understand the perspectives of practitioners. 11 practitioners from 8 different municipalities were interviewed. Cases for the interview study were selected in priority among respondents who gave particularly insightful answers in the survey, but some participants were interviewed simply because they volunteered or were already in touch with the researchers. The interviews were recorded, transcribed, and quotes were classified into key themes (Miles & Huberman, 1994; Vaismoradi, Turunen, & Bondas, 2013). The themes included the overall strategy of the municipality when working with low-GWP construction, available resources, relevant internal skills, collaboration between stakeholders, experience with steering tools to mitigate GWP from construction, future prospects, and perception of the role of local and national authorities.

The cases of Stockholm and Växjö were analysed in more detail. Accounts of how these municipalities have worked with mitigating GWP from construction were written based on interviews and document analysis. The cases were selected to maximize variation, and because they can be considered critical cases. First, the two municipalities exemplify two different approaches to addressing GWP from construction: Stockholm worked with introducing LCA to set performance-based requirements, while Växjö worked more with promoting wood construction, i.e. a specific technical solution. Second, they are comparatively large and have invested time and resources into working with such requirements. Therefore, any challenge they face is likely to also arise in municipalities with less resources and less dedicated policies, and they could provide context-specific information on potential success factors to overcome these challenges.

3.3.3 Investigation of the role of artefacts in decision processes

Another research task focused on factors in and around a development project that enable, constrain and mediate decisions related to sustainable design. This was investigated through case studies of two completed public housing projects in Sweden and two in Cyprus (Paper 5). Initially, the study was designed with a particular interest for the potential integration of LCA tools in real decision processes. Public housing cases were chosen because they represent a type of development projects that is widespread, present in many countries, serving a clear and consistent purpose, and because one collaborator in the project had previous experience as an employee of a public housing organization. Sweden and Cyprus were chosen because they are European countries with different national contexts, including different climates, population sizes and cultures, thus offering a greater insight into the diversity of decision situations in development projects. In Cyprus, one project was selected to represent traditional, mainstream practices in the organization (CY1) and the other to represent more recent practices and higher ambitions in terms of quality and environmental performance (CY2). In Sweden, the intention was to follow a similar rationale for case selection. However, the project selected with higher environmental ambitions lead to major setbacks and several key participants either refused to or were not able to participate. Due to pragmatic concerns, the two Swedish projects selected (SE1 and SE2) are rather mainstream, although both have environmental ambitions above legal minimum requirements. Each case was studied using document analysis and semi-structured interviews.

Documents were analyzed all throughout the study. First, documents such as drawings, models, participant lists, internal guidelines and other documents within the contracting organization were gathered in order to better understand the cases. Then, documents mentioned by the interviewees or which seemed important in light of our preliminary analysis were read, including in particular relevant policy and planning documents.

Semi-structured interviews were carried out with various practitioners in each project and organization, including the management of the organization, project leaders, architects and engineers. Interviewees were selected based on the document analysis and recommendations from other interviewees (snowballing approach). The interviews covered the background of the respondent, their role in the project or the organization, their views on what constitutes “high environmental performance” and related notions for a building as well as what decisions have the most influence on a building’s environmental performance, and finally their experience with LCA and other decision support tools.

I studied the Swedish cases, and another co-author studied the Cypriot cases. Interviews were first analysed by the person who conducted them, and were then also read by the other interviewer in order to conduct a joint analysis. The analysis followed closely the empirical data collected, without applying any pre-existing explanatory framework, following the principles of actor-network theory. One theme that arose from the analysis was the influence of artefacts on decisions related to sustainable design, which became the focus of Paper 5.

4 Results

4.1 Challenges to the implementation of measures to mitigate life cycle GWP

The first research question in this thesis concerns challenges to the implementation of measures to mitigate GWP and resource use in the building sector. Different facets of this issue are addressed throughout the thesis. Paper 1 frames the question by highlighting mitigation strategies and issues that demand further discussion. One such strategy is space sharing, and Paper 3 further explores practical challenges to its implementation. Paper 2 considers the perspectives of local public authorities and challenges to their work with requirements to mitigate GWP in construction. Paper 5 considers the perspectives of public real-estate companies and practical challenges to sustainable design in housing projects.

4.1.1 Issues of interest highlighted by a quantitative model in backcasting

The quantitative backcasting model of buildings' GWP (Paper 1) highlighted particularly significant parameters related to the design, construction and operation of buildings that should be addressed in order to fulfil far-reaching climate targets. Four sets of parameters were developed for the spreadsheet model, each corresponding to a different backcasting scenario and each achieving a 92% reduction in GWP compared to present-day values. Analyses of the model results informed a discussion of key strategies and issues to address for buildings to develop in a way that is compatible with an ambitious climate target.

Thorough decarbonisation of the heat and electricity supply was necessary to achieve the GWP reduction target in all scenarios. This is an already widely discussed and prioritized strategy, and the study confirmed that it is a prerequisite for decarbonisation in the building sector. Although the proportions of different types of power sources differed between scenarios, all scenarios had in common high shares of hydropower and biofuels in the energy mix. However, the modelling also highlighted the fact that a decarbonisation of the energy supply alone would not be enough to achieve far-reaching decarbonisation in the sector as a whole. As buildings become more and more energy efficient and the energy supply less and less carbon-intensive, the relative importance of embodied emissions from construction and renovation increases, as also highlighted in several recent building LCA studies (Anand & Amor, 2017; Birgisdottir et al., 2017; Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013).

The model indicated that it is necessary to also mitigate embodied emissions from construction materials in order to reach ambitious climate targets. In all scenarios, part of this reduction was achieved through changes in construction materials, for instance reducing the impact per kg of concrete by mixing in slag and fly ash to replace cement, using biomaterials such as structural timber and straw bale for insulation, or developing new techniques such as 3D-printing buildings. However, in all scenarios, technological changes were insufficient to reach the emission target. Reaching the target also entailed changes in the amount of construction (e.g. promoting refurbishment instead of new construction) and in the ways buildings are used. In particular, floor area per person was significantly reduced in all scenarios, and was highlighted as a significant parameter in the sensitivity analysis. This optimized use of space took different forms in various scenarios, from space sharing (coliving, coworking and multifunctional buildings) to living in very compact apartments, to remote working. Reducing the demand for space reduces in turn the demand for construction as well as operational energy use.

The modelling also highlighted potential conflicts and trade-offs between GWP mitigation strategies. With a decarbonised energy supply, very extensive energy renovation might not help reduce total GWP. Beyond a certain threshold, the reduction in operational GWP can be compensated by the increase in embodied GWP caused by the renovation measures. Very high energy performance might provide benefits in terms of e.g. resilience and resource preservation, but would not help fulfilling the climate target as it increases embodied GWP. However, this observation is only valid in a context where the energy supply is very low carbon: with the present-day mix in most countries, energy renovation remains a very relevant strategy to decrease GWP. One takeaway of the study is that energy renovation is however insufficient, and that it is also necessary to mitigate embodied GWP.

Moreover, the study lifted a potential trade-off between using bioresources as construction materials and in the energy supply on one hand, and limiting land use and the exploitation of forests on the other. A rough quantification of the use of bioresources in all scenarios did not highlight any obvious issue (e.g. overshooting the carrying capacity of Swedish forests), but the limited scope of the model does not allow drawing far-reaching conclusions. Finally, the study also included a rough quantification of cumulative embodied emissions before the year 2050 caused by the construction and upkeep of buildings and renewable energy power plants. Cumulative embodied emissions, while not daunting, are significant, especially emissions from the construction of PV power plants. This is an important observation considering that the timing of GHG emissions matters when determining their actual cumulative radiative forcing at a given year (Collinge, Landis, Jones, Schaefer, & Bilec, 2013; Levasseur, Lesage, Margni, Deschênes, & Samson, 2010). This indicates the importance of considering GHG emission targets not only in terms of a level to be reached at a certain year, but also in terms of a budget of cumulative emissions over time, as also highlighted by Habert et al. (2020).

Overall, the model supported a discussion of priority areas in GWP mitigation strategies for the building sector, and spotlighted less discussed strategies and issues to address to reduce GHG emissions in the building sector. Meeting ambitious climate targets require a combination of strategies. While decarbonisation of the energy supply and energy efficiency renovation are necessary components of a transition towards a low-carbon building sector, there is a need to also mitigate emissions embodied in construction materials, limit the amount of new construction and use indoor space more efficiently.

4.1.2 Challenges to the implementation of space sharing

Since space sharing was highlighted in the backcasting study as a relevant GWP mitigation strategy that deserves further examination (Paper 1), it was investigated further in an exploratory study (Paper 3). This study was meant to highlight aspects of space sharing that are of particular importance for building users and practitioners, and to consider how to use appropriate metrics to assess performance in shared spaces, and in particular energy performance.

The interview study revealed that for building users, space sharing can be an attractive solution when looking for an apartment or workplace, by providing access to higher quality facilities and advantageous locations at a comparatively cheap price. In some cases, the community itself is seen as an asset, and people seek the opportunity of living or working with the right people. Space sharing and compact living carry the risk of overcrowding and poor living conditions, but this was not apparent in the cases studied. Sharing was enabled by particular characteristics of shared spaces, such as a focus on access to services and on the functions fulfilled by various rooms. “Shareable spaces” were characterized as having overlapping functions, and being flexible and adaptable to various needs. In some cases, users were involved in co-designing the space they were going to use, giving them additional ownership of the space.

Beside the physical space, different forms of organization and decision-making were observed in sharing initiatives, including initiatives driven by an individual, by a collective of users with structured decision processes, or by an external company with little user involvement. More implicit social factors also appeared important. Some sharing initiatives exhibited a strong group identity, e.g. mentioning flatmates or co-workers as a “family”. This was fostered by socialization, common meals and collaboration (both professional and to solve issues faced by the collective). In some cases, deliberate processes were put into place in order to create this group identity and establish a consensus on boundaries and appropriate behavior within the community.

Building sector practitioners mentioned different types of challenges preventing them from working with space sharing. First, at the regulatory level, there are ambiguities in legislations and planning documents, which make it more difficult to build multifunctional or shared buildings. For instance, there are issues regarding the possibility of writing individual contracts for each tenant in housing where most of the space is shared, as well as regarding legal rights, responsibilities and insurance coverage in shared spaces. Multifunctional buildings, i.e. buildings that would combine housing, office space and/or commercial space, face complexities as different building functions are associated with different rules for e.g. accessibility, fire safety, daylight, acoustics and ventilation. Moreover, detailed development plans from the municipality define in advance what types of buildings are to be constructed in an area, and multifunctional buildings might require modifications or exceptions to the development plans.

Second, current practices among developers and real-estate managers create barriers to the implementation of space sharing. This primarily comes down to indicators used for decision support. From a business perspective, property owners usually focus on maximizing rentable floor area and rent per m^2. Sharing space reduces the demand for floor area. While it might increase the value of each m^2 for the owner, this potential benefit is more uncertain and requires a shift in business model (e.g. a service-based model where tenants rent “access to facilities” rather than space, or prices that dynamically adapt to occupancy). From the perspective of building design and performance assessments, decisions often rely on metrics that do not consider occupancy and make space sharing appear suboptimal. For instance, energy performance is assessed in kWh/m^2. Shared spaces might exhibit a higher energy use per m^2, but a lower energy use per person. Moreover, design for flexibility and adaptability might require additional costs or use of materials, but the benefits derived from it are difficult to assess. Therefore, complementary metrics are needed in order to take into account how space is used and encourage a more efficient use of space.

4.1.3 Challenges to the use of environmental requirements by municipalities

The previous section considered challenges to the implementation of a particular sustainability strategy, space sharing, from the perspectives of building users and practitioners. This section addresses a different facet of the first research question. The focus is on the potential role of local public authorities in driving the adoption of GWP mitigation measures. In particular, the thesis investigates challenges to the use of requirements by Swedish municipalities to promote construction with a low GWP (Paper 2).

There are a number of situations in which municipalities could conceivably set environmental requirements in construction. As a public authority, the municipality handles all steps of the planning process:

- Comprehensive plans, which set the overall development strategy, areas to be developed and targets to be reached.

- Detailed development plans, which regulate development in a specific area. They can specify various attributes of buildings to be constructed and are legally binding.

- Land allocation and land exploitation agreements. The former grants a developer the exclusive right to develop on a parcel owned by the municipality (this can be the result of a competition between developers). The latter specifies how the developer will conform to the detailed plan in a parcel that is not owned by the municipality.

- Building permits, delivered to each construction project before the project can start.

Beside their role as public authorities, municipalities also play important roles as property owners. In that role, they can set requirements in a number of processes:

- When organizing contests for land allocation or architectural competitions.

- When selling land, as long as the municipality does not hinder free competition or abuse its monopoly.

- Through a municipally-owned real-estate company managing e.g. public housing projects, school buildings, etc. The municipality sets the objectives that the municipal real-estate company must fulfill through owner directives, and the company can set environmental requirements in its procurement processes.

The survey of Swedish municipalities provided a starting point to investigate how municipalities work with requirements for GWP mitigation. The most common instruments used by municipalities were procurement, dialogue with stakeholders, and the provision of guidance and tools. Very few respondents reported using measures related to the municipality’s role as a public authority. In most cases where municipalities did use such requirements in construction, they worked with prescribing specific designs and materials, but environmental performance requirements were very rare. A statistical analysis revealed links between the municipality’s population (as a proxy for its size and resources) and its work with environmental issues in construction. Municipalities with a dedicated policy document dealing with these issues were significantly larger than municipalities without such a document. Large municipalities implemented more measures than small municipalities, but there was no significant difference between small and medium, or medium and large municipalities.

The interviews allowed for a more in-depth analysis of three types of barriers to the use of LCA-based environmental performance requirements.

First of all, the study identified barriers related to limited LCA-related skills and data: Only the largest municipalities reported internal knowledge of LCA within their organization, but even then it varied between project leaders and the municipalities relied on hiring external consultants. Material inventories and environmental data are often unavailable or of poor quality, leading to unreliable results. Procedures to gather data and carry out assessments are not yet standardized, which hinders comparability.

Furthermore, barriers related to limited time and resources were identified. It is time-consuming and costly to establish new working procedures, train staff, perform LCAs, fix data gaps, etc. A respondent from a smaller municipality mentioned that they don’t have the resources required to build up knowledge. The largest municipalities do have ongoing knowledge-building processes and may take up a role as forerunners in sustainability issues. They consider that they have the means to influence the practices of construction companies and smaller municipalities. There is also a perceived risk that environmental requirements would increase construction costs, limiting buy-in from developers and constructors.

Finally, the study highlighted barriers related to legal uncertainties and a lack of support from other authorities. Some municipalities consider that environmental performance requirements are too complex to be handled at their level and argue that procedures should be established at the national level. It is sometimes unclear whether municipalities are legally allowed to set requirements, and they fear legal prosecution. As a public authority, the municipality is required to follow the Planning and Building Act (SFS 2010:900). A legal block (SOU 2012:86) was introduced to specify that municipalities, in their roles as public authorities, may not prescribe additional requirements that are more ambitious than the building code. However, the legislation is somewhat ambiguous regarding what kinds of requirements are prohibited for public authorities. For instance, it is unclear whether it would be illegal to set requirements on aspects that are not regulated in the building code (such as environmental performance). It is also unclear to what extent this interdiction applies when the municipality establishes detailed development plans, as other paragraphs of the Planning and Building Act indicate that the municipality can set requirements and prescribe specific technical solutions in detailed development plans. Previous studies suggest that many municipalities have used requirements that could be considered illegal according to the legal block (Florell, 2016; Svensson & Torbäck, 2016).

4.1.4 Challenges to sustainable design practices in housing projects

The previous sections highlighted some key issues to address in order to mitigate GWP in the building sector, and considered challenges to the implementation of two particular types of practices that could help mitigate GWP: space sharing and the use of environmental requirements by municipalities. This section takes a broader perspective by considering challenges to sustainable design as a whole, but focuses on understanding the perspectives of actors and actual decision situations occurring throughout development projects. Case studies of public housing projects in Sweden and Cyprus highlighted particular challenges linked to the role of artefacts throughout the project (Paper 5).

Many aspects of building design are determined or strongly influenced by artefacts external to the project. Some artefacts enforce minimum demands in terms of energy- or environmental performance. Such demands and requirements were mentioned as particularly important: many actors were willing to work with sustainable design practices and use tools such as LCA, but only to the extent that this is required by the law, by the management of their organization or by their client. In Cyprus, the EU Energy Performance of Buildings Directive (EPBD) is a major driver to changes in energy performance, as it provides a background level of performance requirements. The EPBD was the only artefact enforcing a minimum level of energy performance. On the other hand, in Sweden, both cases studied had energy- and environmental performance requirements going above legal minima. These were also codified in various artefacts, such as internal handbooks and design instructions in the company, environmental databases of construction products, the Miljöbyggnad certification, and requirements set by the municipality in e.g. detailed development plans.

Artefacts also restrict the range of possible design options. The studied public housing organizations have to choose affordable design options. The Swedish municipal housing companies also base their investment decisions on calculations of profitability with a 15-years time horizon, leading them to use low-maintenance materials such as bricks. Moreover, as public organizations, public housing organizations have to follow regulations on public procurement, forcing them to use options that are widely available on the market. Finally, requirements in development plans can constrain the choice of materials. Some detailed plans directly require the use of particular materials for e.g. facades and roofs, for aesthetic reasons. Height requirements can also indirectly hinder the use of timber structures, as timber buildings tend to require thicker floor slabs and are therefore taller (for the same number of floors and ceiling height). Altogether, the choice of design options takes place within a space constrained on one hand by performance requirements that enforce a certain consideration of sustainability criteria, and on the other by constraints related to budget, public procurement regulations, development plans, etc., which can prevent the use of particular sustainable design options.

Several other artefacts simplify the design process, providing standardized default design options and replacing extensive assessments with simple choices between a few predefined options. Thus, part of the design process is outsourced: Guidelines and default options are developed upstream of the project, and the selected designs are then used in all new projects. In early design stages, standard drawings have been used in the Cypriot housing organization, while one Swedish project leader used a checklist of sustainable design measures to consider what could be feasible in each project. In later design stages, the Cypriot organization relies on an internal database of standardized technical specifications to select materials and installations. The Swedish municipal housing companies use internal documents called “construction handbook” or “design directions”, which contain extensive descriptions of designs, materials and technical solutions to be used in all projects. Moreover, they relied on databases of environmental impacts (SundaHus and Byggvarubedömningen) to select construction products, which outsource the assessment of environmental performance. Multiple interviewees emphasized this need to simplify design choices, mentioning that they already manage large amounts of complex information and need organizational tools and streamlined procedures to consider additional issues such as environmental performance. A challenge to the adoption of sustainable design practices is therefore the need to manage complex information and processes. This shows the importance of providing simple and streamlined decision support tools, and suggests that some key decision situations determining a project’s environmental performance happen not within the project itself, but upstream of the project, when these databases, handbooks, checklists and default solutions are designed.

In Cyprus, designers were only required to follow legal minimum requirements in terms of energy- and environmental performance. No other artefact was providing direct requirements or guidelines related to sustainable design. As a result, designers' work with sustainable design depended on their personal experience, motivation, skill, knowledge of sustainable design and ability to convince their peers. A Swedish practitioner indicated that until the recent introduction of an internal construction handbook, knowledge transfer within the organization was also informal and based on personal experience. However, in the Swedish cases, many sustainability criteria are now strongly codified, objectified and enforced in various interconnected artefacts, notably the Miljöbyggnad certification, environmental databases for construction products, and internal construction handbooks.

However, while various artefacts enforce, limit and simplify decisions related to sustainable design, the case studies revealed a complex interaction between these artefacts and the agency of human actors. Requirements, constraints and guidelines are bent, departed from and adapted to each situation on a case-by-case basis. Thus, in the Cypriot cases, standard drawings exist, but they are no longer applied identically in all projects, they are instead adapted to each case. Similarly, in the Swedish cases, the construction handbook is used to different extents by different projects leaders. Exceptions are also made to the use of environmental databases to select construction products: Products with an insufficient environmental grade are sometimes selected in the absence of suitable alternatives, with the approval of the project leader. Finally, actors influence in return the artefacts they use and the directives they follow. For instance, managers in a Swedish municipal housing company mentioned that they influence the content of directives they receive from the municipality, by being part of various working groups within the municipality. Therefore, requirements, standards and similar artefacts do not necessarily condition design decisions through straightforward cause-and-effect relationships. Rather, they are better understood as mediating design decisions, which result from a chain of human and non-human mediators.

4.2 Assessing environmental performance for decision support

The second research question in this thesis focuses on the role of quantitative assessments of environmental performance for decision support. Some examples of the roles played by such assessments were already hinted at in the previous section. Paper 1 exemplified how the use of a quantitative model can support a discussion of relevant strategies in backcasting. Paper 3 highlighted that conventional performance metrics normalized per unit floor area do not incentivize space sharing. Papers 2 and 5 investigated the potential use of LCA in requirements from local public authorities and in development projects respectively. This section will explore further issues related to the practical implementation of quantitative assessments of environmental performance.

4.2.1 Sensitivity of LCA outcomes to methodological choices

LCA is starting to be used more and more broadly in certification, and there are recent initiatives to introduce it in green procurement and regulation (e.g. mandatory declarations of climate impact). However, to reliably support a more sustainable design of buildings, LCA results must be precise and accurate. This section examines one particular facet of this issue, namely the sensitivity of façade LCA outcomes to methodological choices related to maintenance and replacement (Paper 4).

An initial literature review highlighted some of the main methodological issues related to maintenance and replacement in building LCA. First, the scope of maintenance and replacement processes included (modules B2 to B5 in the EN 15978 terminology) is ambiguous and varies between studies, i.e. studies are more or less extensive in the amount of processes they cover (Chastas et al., 2018; De Wolf, Pomponi, & Moncaster, 2017; Dixit, 2018). Moreover, different studies use different reference study periods (RSPs): the contribution of maintenance and replacement processes is larger when the RSP is longer (Goulouti et al., 2020; Häfliger et al., 2017; Hoxha et al., 2016). Another issue is linked to the assumed frequency of maintenance and replacement operations. Multiple methods can be used to estimate the service life of a building element (Grant, Ries, & Kibert, 2014) and service life values found in the literature show very broad variations (Dixit, 2018; Hoxha, Habert, & Le Roy, 2014). Finally, different methods might be used to calculate the number of replacements during the RSP. Some systems (e.g. the EN 15978 norm and the DGNB certification) prescribe a round-up number of replacements (a product with a 30 years service life is replaced 3 times in 100 years) while others (e.g. the French E+C- label) use a fractional or annualized number of operations (a product with a 30 years service life is replaced 2.33 times in 100 years).

Subsequently, a comparative case study of seven different façade alternatives, following different combinations of methodological and data-related choices, revealed the influence of these choices on LCA results. The first aspect investigated was the influence of the reference study period of the LCA. Figures 2, 3 and 4 indicate the results of the LCA over 50, 100 and 200 years respectively.

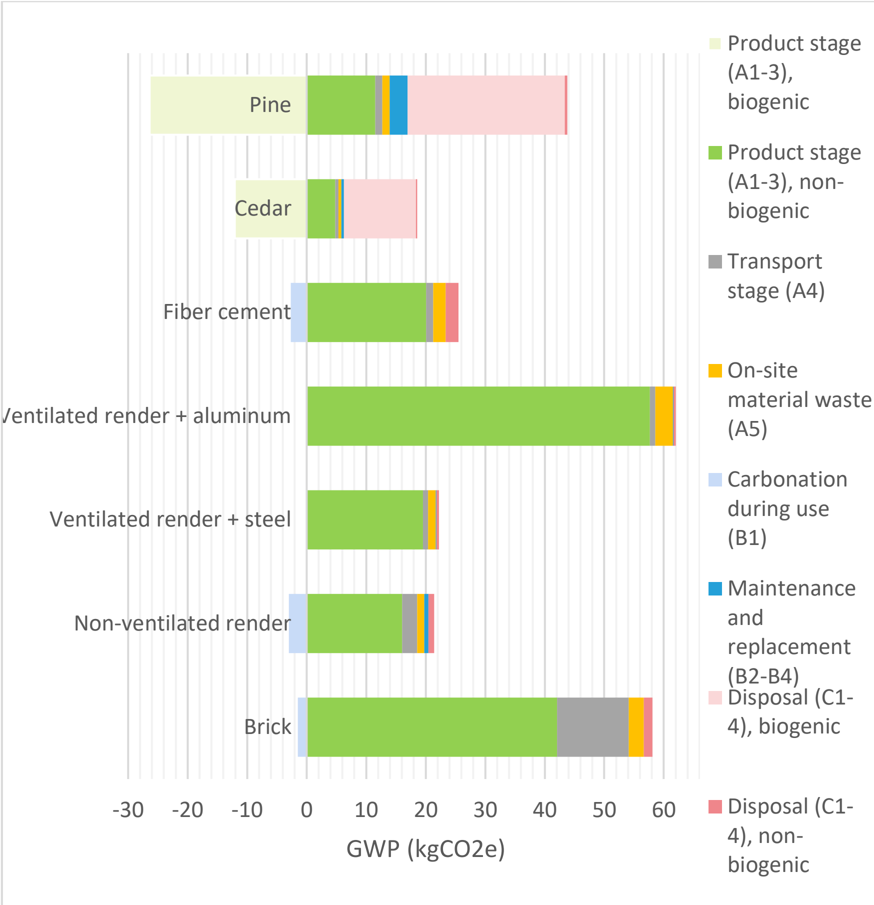


Figure 2 - Life cycle GWP of all façade alternatives over 50 years (Paper 4)

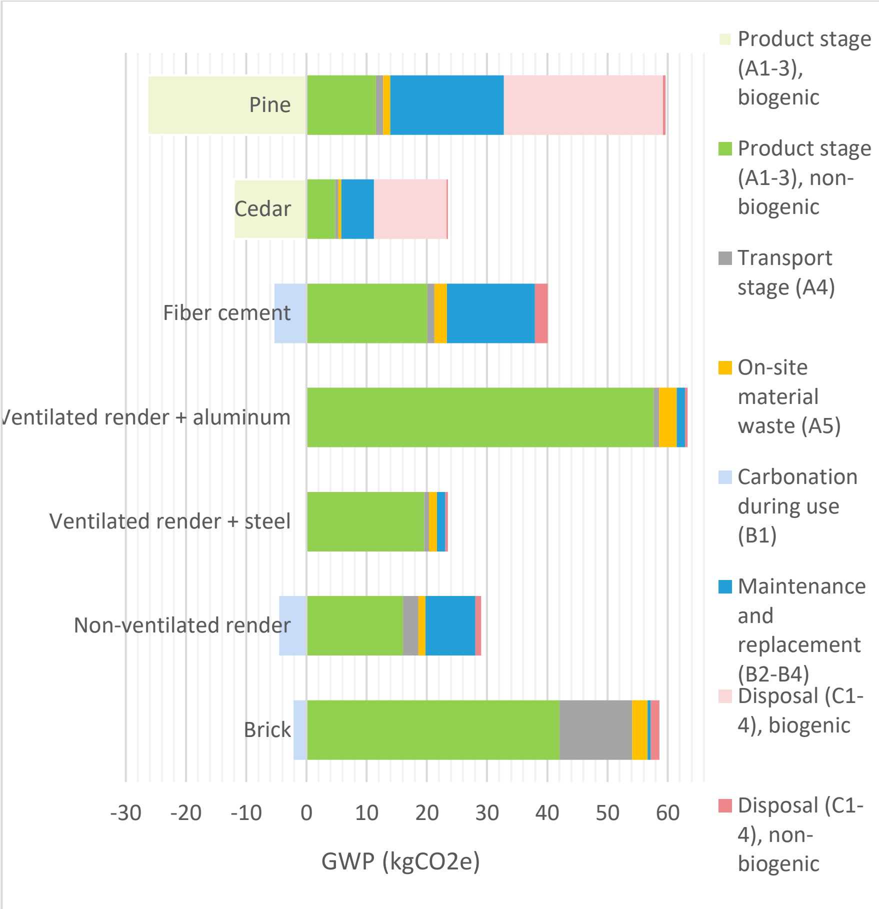


Figure 3 - Life cycle GWP of all façade alternatives over 100 years (Paper 4)

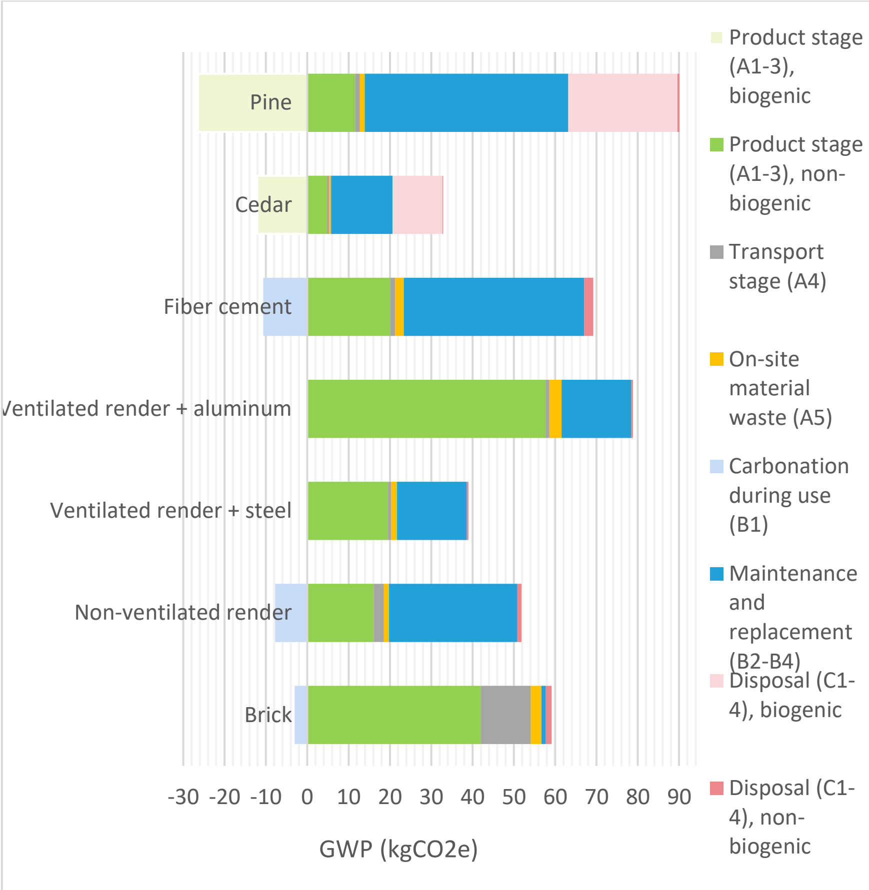
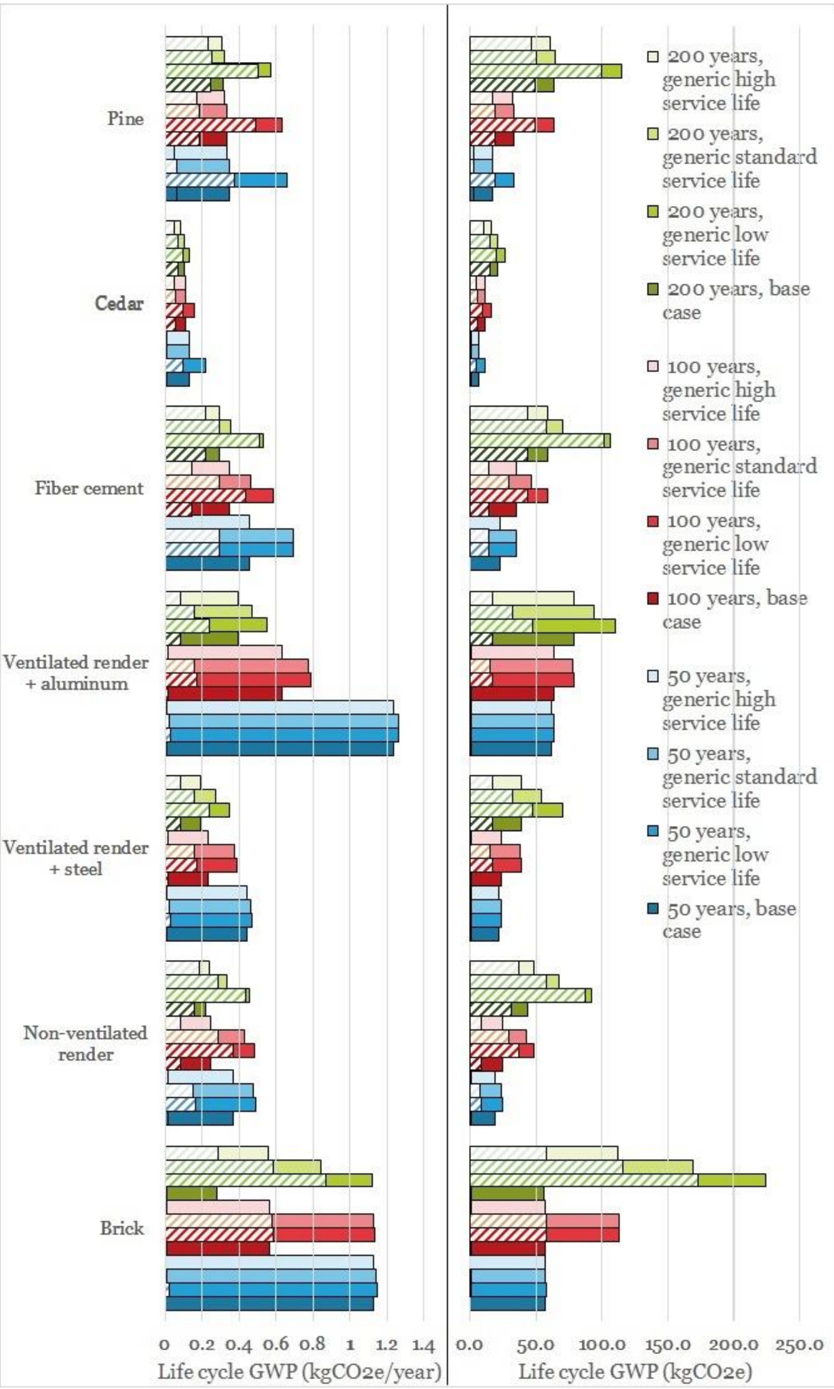


Figure 4 - Life cycle GWP of all façade alternatives over 200 years (Paper 4)

The choice of RSP significantly influences the ranking of alternatives, although the cedar clapboard panels had the lowest GWP and the ventilated render façade with aluminum profiles the highest GWP in every scenario. Low-maintenance options (e.g. brick) rank better over long RSPs, and high-maintenance options (e.g. painted pine cover boards) rank worse. Over a 50 years RSP, maintenance and replacement processes are negligible for all alternatives except the pine cover boards. Over longer RSPs, the relative influence of maintenance and replacement processes increases, and these processes become a key hotspot for some alternatives.

The second aspect investigated was the choice of service life data. Figure 5 indicates the results of the case study when using low, standard and high generic service life values from the literature (Erlandsson & Holm, 2015) instead of values from manufacturers (base case). Values are reported both for the total RSP, and normalized per year (i.e. divided by the RSP).



Pine
Cedar
Fiber cement
Ventilated render + aluminum
Ventilated render + steel
Non-ventilated render
Brick
0 0.2 0.4 0.6 0.8 1 1.2 1.4
Life cycle GWP (kgCO2e/year)
0.0 50.0 100.0 150.0 200.0 250.0
Life cycle GWP (kgCO2e)
200 years, generic high service life
200 years, generic standard service life
200 years, generic low service life
200 years, base case
100 years, generic high service life
100 years, generic standard service life
100 years, generic low service life
100 years, base case
50 years, generic high service life
50 years, generic standard service life
50 years, generic low service life
50 years, base case

Figure 5 (opposite) - Life cycle GWP using generic service lives versus service lives from manufacturers. The hashed area represents the contribution of modules B2-B4; the filled area represents all other modules. (Paper 4)

For some of the alternatives, there is a very significant difference between using generic service lives from the literature and using values from manufacturers, especially over longer RSPs. Service lives obtained from manufacturers are almost always higher than generic standard service lives, and sometimes even higher than high generic service lives. The difference is particularly important for bricks, where the calculated GWP is considerably higher over long RSPs when using generic service life data.

The third aspect investigated was the choice of method for calculating the number of maintenance and replacement operations, i.e. using either a round-up or a fractional number of operations. In cases where there is no replacement operation or the RSP is a multiple of the replacement period, there is no difference between the two methods. In some other cases, the difference is small. However, the fractional method leads to a significantly lower calculated GWP in specific cases, when a major replacement operation happens shortly before the end of the RSP. Therefore, the choice of calculation method for maintenance and replacement might not make a significant difference in average, but it can be very significant in specific cases.

Overall, these methodological issues can influence the outcome of the assessment, and therefore the recommendations given and the kinds of hotspots and issues to be prioritized. Therefore, for LCA to provide reliable guidance and decision support, there is a need to use harmonized approaches to ensure that studies are comparable. Moreover, reliable service life- and environmental data are needed.

4.2.2 Complementary metrics for shared spaces

One of the challenges to the implementation of space sharing identified in Paper 3 was the fact that building performance metrics, and in particular energy performance metrics, are usually expressed per m^2 floor area. Such metrics do not consider how space is used, and might even be detrimental to shared spaces. If a building is used more intensively, energy use per m^2

might be higher, although energy use per person might be lower. Therefore, using exclusively metrics normalized per m^2 does not incentivize efficient use of space. There is a need to investigate how using other energy performance metrics could allow practitioners to consider how space is used when assessing building performance. This question was briefly explored through a literature review of complementary energy performance metrics that consider occupancy and space efficiency (Paper 3).

The review exemplifies several different types of energy performance metrics considering occupancy. Some metrics normalize the results based on an indicator of activity instead of floor area, for instance energy use per person, per person-hour or per euro of market value (Forsström et al., 2011; Sekki, Airaksinen, & Saari, 2015, 2017). Other indicators combine floor area and occupancy, often by dividing the area-normalized indicator by another variable (e.g. energy use per m^2 and hour of use, or per m^2 and person-hour) (Huovila, Tuominen, & Airaksinen, 2017; Lindberg et al., 2018). More complex metrics include e.g. efficiency of the layout and weighted sums of different indicators (Escrivá-Escrivá, Álvarez-Bel, & Peñalvo-López, 2011; Huovila et al., 2017). Finally, the building can be compared with a benchmark of similar buildings with similar use patterns (Kontokosta, 2015).

In practice, different metrics are used for different purposes, e.g. to assess how well a building is operated or how a change in occupancy is affecting energy use, to identify issues causing abnormal energy use or opportunities to optimize operation, to assess subsystems such as ventilation that depend on occupancy, etc. Therefore, different situations call for complementary metrics with different scopes, variables and resolutions (O'Brien, Gaetani, Carlucci, Hoes, & Hensen, 2017). However, there is a lack of studies of appropriate indicators for certain types of buildings (e.g. commercial buildings) and certain decision situations (e.g. to inform decisions in the design phase).

Although the review focused on energy performance metrics, similar issues are relevant in LCA when choosing a functional unit. Normalizing LCA results per m^2 heated floor area is the most common solution, but other functional units have been used to consider occupancy, including e.g. normalizing LCA results per person (Bastos, Batterman, & Freire, 2014).

Overall, building performance metrics consider or disregard different aspects of building design and operation depending on the variables they include. A comprehensive mitigation of buildings' environmental impacts will require addressing not only how buildings are constructed, but also how they are used, refurbished and decommissioned. The latter aspects are mostly absent of conventional building performance metrics. Introducing complementary metrics is a way of making visible key aspects of particular sustainability strategies (such as occupancy and space efficiency) that were previously hidden from decision situations.

4.2.3 Role of environmental performance assessments to steer towards lower environmental impacts

The various studies in this thesis identify multiple roles played by environmental performance assessments. First, environmental performance requirements can be used in e.g. procurement and regulation to directly enforce a maximum level of environmental impacts. Interviews with practitioners in public housing organizations (Paper 5) highlighted the existence of requirements (e.g. energy performance requirements) from the building code, development plans and demands from the client as important drivers to enforce a certain level of work with sustainable design. Designers mentioned a willingness and ability to work with sustainable design, but only if this is required of them. Although such requirements can be prescriptive, e.g. require the use of a particular design solution, requirements based on assessments of environmental performance allow for flexibility and innovation and ensure that the desired outcome is reached. Municipalities could play a driving role and introduce environmental performance requirements in construction, for instance in land allocation- and architectural competitions, in their own procurement practices or possibly in detailed development plans. However, such uses of environmental performance requirements are still very rare. Municipality officials mentioned multiple challenges, including a lack of time, resources, skill and data to carry out and monitor environmental performance assessments, as well as ambiguities regarding whether such requirements would be legal or not (Paper 2). Designers in housing companies mentioned similar challenges and strongly emphasized the need for streamlined and simplified procedures (Paper 5). One potential strategy for the progressive introduction of environmental performance requirements, suggested in Paper 2, is to start by only requiring the provision of inventory data for new projects, and then progressively requiring the calculation of environmental impacts, in order to bridge knowledge- and data gaps.

When it comes to the use of environmental performance assessment in design, the analysis of design processes in public housing projects (Paper 5) suggests that many key design decisions are taken upstream and outside of the project. For instance, standard drawings, handbooks and design directions are developed within the organization, and then provide default solutions used in new construction projects. Moreover, practical constraints such as scheduling and budget leave only very limited opportunities to assess environmental performance within the project. Consequently, while some respondents considered that LCA could be a useful tool to steer towards sustainable design, some mentioned that it would be more appropriate to use LCA not within each project, but rather at the level of the organization, e.g. to update design guidelines and standard solutions. Considering the respondents' stated need for streamlined and simplified procedures, such assessments also need to be simple, and perhaps in the first place limited to particular building elements, indicators or life cycle stages. Therefore, a systematic use of LCA integrated in the design process does not necessarily reflect the reality and constraints of design situations. In order to efficiently steer towards more sustainable practices, environmental performance assessments such as LCA must be adapted to real use situations.

The qualitative investigation of design processes (Paper 5) also revealed more complex effects of environmental performance assessments. In particular, performance criteria from the Miljöbyggnad certification and databases of environmental performance for construction products (such as SundaHus and Byggvarubedömningen) deeply influence actors' understanding of what constitutes sustainable design. Both can be considered as boundary objects, i.e. objects that enable communication and cooperation, because they provide a shared language and a basis to construct shared meaning (Georg, 2015; Nicolini et al., 2012). The Miljöbyggnad certification criteria and target levels influence actors' views on sustainability, what they focus on, and their ambition levels, even in projects where the Miljöbyggnad certification is not used. Because Miljöbyggnad is widely recognized and has become a reference point for what constitutes sustainable buildings in Sweden, some construction projects are designed *according to Miljöbyggnad*, even though they are not certified. One of the Swedish municipal housing companies received a directive from the municipality asking them to be at the forefront in terms of environmental sustainability, and operationalized this directive by certifying all new projects with the Miljöbyggnad Silver certification.

Therefore, decision makers indexed their ambitions on the Miljöbyggnad criteria and levels, and ambiguous environmental ambitions were translated and operationalized by using Miljöbyggnad criteria. Thus, Miljöbyggnad becomes the de facto definition of a sustainable building when actors need concrete reference points.

Similarly, environmental databases for construction products such as SundaHus and Byggvarubedömningen played an important role in mediating actors' definitions of what constitutes sustainable construction products, by outsourcing the assessment of environmental performance, simplifying it and providing a single score for each product. Designers do not assess environmental performance for construction products, but simply look up the product's "grade" in the database, a single-score sustainability indicator aggregating multiple criteria. The complexity of the assessment is therefore black-boxed, not directly visible to the users. It is only in problematic cases, e.g. when the contractor requests the authorization to use a product with a poor grade, that the project leader or sustainability strategist examines the underlying criteria in more detail. This simplified assessment is necessary to provide users with a streamlined way of considering environmental performance when selecting construction products. However, some users rely on the database without understanding how environmental performance is assessed. For instance, a contractor considered that he was already selecting products with a low GWP since he was selecting products with a good grade in the database. However, both databases focus on local environmental- and health impacts, and aspects such as GWP are not taken into account in a product's grade. These environmental databases determine what aspects of sustainability are taken into account by designers, and hide or reveal various aspects of this issue. This selection is black-boxed and unchallenged. Therefore, it is necessary on one hand to ensure that widely-used tools for environmental performance assessments actually address key environmental issues, and on the other hand to communicate transparently and educate practitioners in order to raise awareness of the underlying criteria behind the tools they use.

This ability of quantitative assessments to hide or reveal certain aspects of building sustainability can also be harnessed to spotlight issues that are less discussed and deserve closer consideration. Thus, using complementary energy performance metrics that take into account occupancy and space efficiency allows bringing forward the issue of how space is used when assessing a building's performance (Paper 3). Moreover, the thesis exemplifies how the use of a quantitative model of GWP in the building sector coupled with a backcasting approach can highlight issues of interest, such as efficient use of indoor space and the importance of mitigating embodied GWP from new construction (Paper 1). Because e.g. floor area per person was a parameter in this quantitative model, it became a matter of concern and a topic of discussion. In that regard, the value of using a quantitative model of GWP in a backcasting study did not lie primarily in the model's accuracy. Rather, the very task of modelling building parameters in all backcasting scenarios contributed to a discussion of how buildings would be constructed and operated in each scenario. This created an interplay between the qualitative formation of images of the future and quantitative estimates of building parameters. The quantification objectified, made concrete and brought forward some aspects of the scenarios that were previously ambiguous, such as use of space and energy performance. At the same time, it "silenced" other aspects of the scenarios, such as people's lifestyles and professional activities.

5 Discussion

5.1 Decision support to help practitioners and policymakers mitigate GWP

5.1.1 Supporting policy discussions and decisions

The thesis provided relevant insights regarding policies to steer towards GWP mitigation in the building sector. First, it explored how quantitative modelling of GWP can support strategic discussions of future scenarios (Paper 1). The use of a bottom-up approach did not allow for a reliable or comprehensive modelling of emissions within the building sector as a whole, but it did have the advantage of being relatable. Parameters in the model could directly be linked to specific aspects of building design and operation in the various future scenarios. The use of a quantitative model combined with a backcasting approach allowed highlighting issues of interest such as efficient use of indoor space and amount of new construction, and bringing them on the agenda. The act of integrating less discussed parameters such as floor area in such a future-oriented model can help questioning current paradigms in the building sector. Varying a parameter in a model is thus a way of questioning and discussing this parameter. Most backcasting studies either rely on developing images of the future through qualitative and participatory methods (Doyle & Davies, 2013; Svenfelt et al., 2011), or use models for quantitative demonstrations (Emodi, Chaiechi, & Alam Beg, 2019; Fujino et al., 2008; Gomi et al., 2011). While quantitative models in futures studies often aim to provide accurate predictions, the thesis showed how a quantitative model could be used to support more qualitative and normative tasks and contribute to the development of images of the future that challenge existing paradigms. The relevance of combining quantitative and qualitative methods so that they inform and complement each other throughout the backcasting project has been highlighted by Pereverza et al. (2019).

The thesis also highlighted the importance of appropriate policy measures to support the implementation of environmental impact mitigation practices. National regulations on energy- and environmental performance and demands from local public authorities play an important role in ensuring that designers consider particular aspects of sustainability (Paper 5). The thesis particularly highlighted the extent to which municipalities could set requirements to mitigate GWP in construction. Some Swedish municipalities already steer building design in particular directions, through the use of prescriptive of performance requirements (Paper 2). This is strongly dependent on the country: Sweden follows a plan-led, coordinated and structured approach to planning, driven by municipalities, but other countries have widely different cultures regarding planning and the roles of local authorities (Othengrafen, 2010).

The thesis identified barriers to the use of LCA-based environmental performance requirements by municipalities, related to a lack of skills, data, time, resources and a fear of legal prosecution if they set requirements in planning documents. The barriers identified are consistent with previous literature highlighting knowledge as a key success factor in green procurement (Testa, Annunziata, Iraldo, & Frey, 2016; Testa, Iraldo, Frey, & Daddi, 2012; Walker, Di Sisto, & McBain, 2008), and cost as a challenge in green procurement (Appolloni, Sun, Jia, & Li, 2014) and local energy and climate strategies (Wretling et al., 2018). Previous literature also highlighted the importance of appropriate guidance and legislation at the national level, in order for local authorities to successfully work with energy and climate issues (Reckien et al., 2018; Wretling et al., 2018).

Environmental performance requirements were suggested as suitable solutions to ensure a certain level of environmental performance while allowing for flexibility and innovation, but it should be noted that they have been associated with complications and high monetary and time costs (Kadefors, Lingegård, Uppenberg, Alkan-Olsson, & Balian, 2021). Still, a procedure for the introduction of environmental performance requirements in municipalities was proposed (Paper 2), based on the progressive introduction of information requirements. After the municipality gathers appropriate resources and support, the municipality could require developers to provide inventory data for new projects. The municipality could provide standardized tools to support the developers, and progressively require the provision of environmental data in addition to inventory data, in order to fill both knowledge and data gaps.

Despite the relevance of Swedish municipalities in steering sustainable practices, it could be argued that some of these challenges are better addressed at the national level, which can make use of more resources. Furthermore, standardization at the national level could provide legitimacy, predictability and facilitate the dissemination of sustainability requirements (Kadefors et al., 2021). In recent years, the introduction of a national database of default environmental data for construction materials and of a standardized climate declaration method in Sweden have already partially addressed data and knowledge gaps (Swedish National Board of Housing Building and Planning, 2021).

However, regulations can also create barriers to certain practices, even though policymakers had no intention to do so. Thus, regulations and plans where shared and multifunctional spaces do not fit in pre-existing categories create challenges to space sharing projects and uncertainties about what rules apply in such buildings (Paper 3). Similarly, there are ambiguities about the extent to which municipalities can set environmental requirements in construction (Paper 2). Sometimes, these barriers are a side effect of the regulation’s main purpose, e.g. height requirements in development plans can hinder the adoption of timber frames (Paper 5). Here too, appropriate guidance and legislation at the national and local levels are important to address challenges to sustainable practices. Public authorities could create a demand for sustainable buildings through requirements in regulations and development plans, and provide a standardized framework for how sustainability shall be assessed. The introduction of a mandatory declaration of GWP for new building projects in Sweden is an example of the latter, as are requirements on energy performance or local environmental toxicity in the building code. These legal requirements influence in turn the content of voluntary assessment tools, as for instance the Miljöbyggnad certification where some criteria are indexed on the building code (Paper 5).

Such standardized frameworks for sustainability assessment objectify the vague concept of sustainable buildings and render it actionable by actors. This is crucial, since different actors in the building sector have widely different definitions of sustainable buildings, and since they expressed a strong need for simplification and streamlining of their work with sustainable design, due to limited time, resources and LCA-related knowledge (Paper 5). Practitioners’ work with building sustainability depends on how the ambiguous concept of sustainability is translated and transformed at the various steps of a project (Schröder, 2018). Detailed policies can allow public authorities to frame this process to some extent, and to “govern from a distance” the question of building sustainability (Rydin, 2013). More concretely, standardized sustainability criteria also provide legitimacy and predictability on the market, which facilitates their adoption by practitioners (Kadefors et al., 2021).

Finally, policymakers must be mindful of the side effects of these standardized ways of assessing sustainability. They influence actors' understanding and ambitions in terms of sustainable building design, and hide or reveal particular aspects of the issue of sustainability (Paper 5). Standardized sustainability assessment tools and certifications create "black boxes" where sustainability criteria are unchallenged, taken for granted. This is necessary to enable actors to work with sustainable design, but it implies a need for caution when creating the black box itself. For instance, the upcoming mandatory declaration of GWP for construction projects limited to the product stage, transport and on-site processes might spotlight the importance of reducing embodied GWP, but this partial assessment must not lead to burden shifting towards later stages of the life cycle.

5.1.2 Supporting building sector practitioners

The thesis provided relevant insight for building sector practitioners regarding drivers and challenges to sustainable practices. The existence of clear demands from clients in construction projects and sustainability criteria in procurement are important drivers for sustainable practices, as some actors default to following these requirements (Paper 5). This is consistent with previous literature on green procurement (Lam, Chan, Chau, Poon, & Chun, 2011; Wong, Chan, & Wadu, 2016). However, previous literature also highlighted an important role for suppliers in driving the adoption of sustainable practices, by ensuring that sustainable products and services are available on the market (Brammer & Walker, 2011; Wong et al., 2016). The case studies reported in Paper 5 provided a clear example of a contractor driving the adoption of sustainable practices: a housing company established a strategic partnership with a contractor who had extensive internal knowledge in environmental assessments, enabling the housing company to start implementing environmental assessments in all their new projects. This result was not reported in Paper 5 as it was beyond the scope of the paper, but provides interesting material for further analysis.

Appropriate assessment tools are needed in order to take into account sustainability in decisions related to building design and operation. Relying on a particular tool will hide or reveal particular aspects of sustainability depending on the criteria used by the tool, which are sometimes "black boxed", i.e. not examined by practitioners (Paper 5). From a theoretical point of view, the role of quantification in hiding or revealing various issues, creating categories that did not previously exist and eliciting action by reducing the reliance on individual judgment has been previously underscored by Espeland & Stevens (2008). They mention the need to better understand such qualitative effects of quantification. It can be argued that it is particularly important to examine these effects in the context of sustainability assessments, as they relate to major societal challenges.

From a practical point of view, designers of widespread sustainability assessment tools and certification systems should be mindful of what definition of sustainability their products embody, and of their foci and "blind spots". For instance, the Miljöbyggnad certification system in Sweden includes criteria related to daylight and indoor climate, embodying a definition of sustainable buildings that does not sacrifice the well-being of users. However, it does not include any indicator related to occupancy or maintenance needs, so its definition of sustainability leaves these operational aspects invisible, for better or worse (Sweden Green Building Council, 2020a). Conversely, practitioners should be aware of what issues they address or ignore when selecting an assessment tool or a set of criteria. The thesis showed that conventional metrics for e.g. energy performance ignore important aspects of sustainability, such as occupancy and efficiency in the use of space (Paper 3). Paper 3 contributes to solving this problem by presenting a variety of metrics to consider space efficiency and occupancy. As different information might be needed in different decision situations along a project and for different decision makers, using a combination of metrics can provide a more comprehensive picture than any single metric. Although the focus of the review in Paper 3 was on energy performance metrics, the same results apply to the choice of functional unit in building LCA (Chau, Leung, & Ng, 2015). Different functional units and different kinds of LCA data might be needed in different decision situations.

More broadly, foregrounding the issue of space efficiency is a way of bringing back into the discussion the issue of how buildings are used and what function they provide. Commercial practices might need to change in order to address some aspects of sustainability. Indeed, floor area per person and amount of new construction were highlighted as important parameters to reduce GHG emissions in the building sector (Paper 1), but companies usually operate based on a model that values new production and maximizes rentable floor area (Paper 3). One possible solution could be the introduction of service-based business models to supply services such as storage or cooking equipment (as suggested by a workshop participant in Paper 3).

However, the thesis also highlighted limitations to the use of environmental performance assessments in construction projects. Certain types of projects (e.g. public housing) are under tight constraints in terms of time and budget, and there doesn't appear to be suitable occasions to use a tool such as LCA proactively, to support design decisions within the project. Many design choices are actually not made within the project itself, but ahead and outside of the project, when actors develop standard typologies, default design solutions and internal handbooks describing solutions that are used in all new projects (Paper 5). Within a construction project, there is a need for simple and streamlined procedures as well as organizational tools to help practitioners integrate sustainability in their work, since they already deal with large amounts of complex information. In situations with relatively standard designs (such as housing) and limited resources, LCA and similar tools might be better used at the level of the organization, when defining these default design solutions, rather than within each individual project. This echoes differences between prescriptive and performance-based criteria mentioned in Paper 2 and in the green procurement literature (Kadefors et al., 2021). Basing all design decisions on assessments of environmental performance seems ideal from a point of view of innovation and optimization, but does not necessarily fit the real-life constraints of construction projects, in terms of cost, time, skill, etc.

The thesis also highlights the importance of understanding the implementation context of mitigation measures. When standardized solutions or environmental performance criteria are implemented in a building project, they are bent, interpreted and adapted by practitioners, and aspects such as practitioners' agency, experience and motivation come into play (Paper 5). In the case of space sharing, social aspects related to group cohesion are an important success factor (Paper 3). A building project is a complex system, and an isolated analysis of each individual element risks giving only an incomplete picture of the dynamics at play. Therefore, the design of sustainability assessment tools and other measures must be informed by a holistic understanding of decision processes in the building sector.

Insights can be gained by combining different theories and paradigms when studying such complex phenomena (Geels, 2010; Gioia & Pitre, 1990; Lewis & Grimes, 1999). Schröder (2018) uses the concept of translation to show how the concept of sustainability evolves and is enacted throughout a construction project, via a network of human actors and artefacts. This understanding could be complemented by insights on how cultural differences play into development practices in various countries, as Othengrafen (2010) showed that cultural differences are reflected in differences in planning practices. Notions of habits, rule-following and legitimacy found in institutional theories of decision making could also be relevant to analyze situations of seemingly non-rational decision making (Brunsson, 2007; March, 1994; Viking, 2017).

5.2 Quantitative assessments of environmental performance

5.2.1 Implementation of life cycle assessment

Although only Paper 4 is an LCA study per se, LCA has been an important topic across the entire thesis. The thesis examines both quantitative issues regarding the accuracy and precision of LCA results, and qualitative issues regarding the current and potential use of LCA in policymaking and building projects. From a quantitative point of view, the thesis investigated the influence of methodological issues related to maintenance and replacement in the LCA of building façades. While the same façade had the lowest impact in every single scenario, the length of the reference study period (RSP) significantly influenced the ranking of façade alternatives. Such an issue is important in a context where LCA is entering regulation and standardization, considering that most LCA frameworks in Europe use a RSP of 50 or 60 years, including the EU framework Level(s) (Dodd et al., 2021). This choice of RSP does not necessarily reflect the building's technical service life, and is somewhat arbitrary. A common argument is that after 50 or 60 years, the building might be extensively refurbished (and not demolished), which corresponds to the start of a new life cycle. Still, in most assessments with a 50-60 years RSP, the impact of products with a longer service life is accounted for at 100% even though the products might still be used after the end of the RSP. This approach implies that an LCA for a refurbishment project would consider reused materials as having no impact, since the full impact of these materials has already been included in the previous life cycle. This would promote the reuse of materials. A short service life also has the benefit of minimizing uncertainty about the future, and promotes an earlier reduction of emissions, which matters since the timing of emissions influences their actual impact on the climate at any given year (Collinge et al., 2012; Levasseur et al., 2010; Su, Li, Zhu, & Lin, 2017). On the other hand, a longer service life would encourage the use of durable, low-maintenance materials. Another solution to encourage the use of durable materials could be to use different accounting conventions for reuse and recycling. For durable products used beyond the RSP, a fraction of the impact could be deduced from the initial LCA, and instead accounted in the LCA of the future refurbishment project where the product is reused (Eberhardt et al., 2020).

The thesis also addressed issues related to data quality in building LCA. Considerable discrepancies were found between service life data from practitioners and generic data from the literature. For some materials, there were even significant discrepancies in generic environmental data between different databases (in particular for wood, where values in the Ecoinvent and Swedish BM databases were an order of magnitude lower than values in e.g. the Ökobau database). Part of these discrepancies can be explained by the fact that different sources might represent different products or production processes, but differences in methodological choices and assumptions could also play a role. Prior to Paper 4, another study (not included in the thesis) used a Monte-Carlo analysis to analyze the sensitivity of LCA results to service life uncertainty for roof materials (Francart & Malmqvist, 2020). However, standard deviations for service lives found in the literature were extremely high, indicating that available statistical data might not be of high enough quality to draw far-reaching conclusions. It was a conscious choice to avoid using a Monte-Carlo analysis for Paper 4, in order to avoid giving a false sense of precision and confidence in the results (Heijungs, 2019). A broader use of LCA in e.g. regulation requires the use of robust and reliable data, both for service lives and environmental impacts. In Sweden, there is a recent attempt to address this issue through a database of generic GWP data for various materials (Swedish National Board of Housing Building and Planning, 2021). For service lives, the Swiss database DUREE allows for a statistical treatment of service lives (Goulouti et al., 2020).

Finally, the thesis showed how methodological choices related to calculating the number of maintenance and replacement operations (round-up or annualized) could influence the outcome of the LCA. While this difference is likely to be inconsequential at the building level, it can make a difference if LCA is used to select a specific building element. Other methodological issues have even more influence on LCA outcomes. This is particularly the case of the modelling of the electricity supply, where methodological differences related to geographical scope, temporal resolution, future scenarios and calculation methods create major differences in the calculated impact of operational energy use (Clauß et al., 2019; Pannier, 2017; Roux, Schalbart, Assoumou, & Peuportier, 2016). Comparative cases studies have shown that different variants of LCA methods are used in different countries, assessment systems or projects, leading to significantly different results for the same building (Frischknecht et al., 2019, 2020). Therefore, more than just providing robust generic values for service lives and environmental data, there is a need to harmonize methodological approaches in order to use LCA more broadly for e.g. regulation.

5.2.2 Qualitative understanding of the role of environmental performance assessments

Various ways of assessing quantitatively the environmental sustainability of buildings have been addressed throughout the thesis: a spreadsheet model of GWP in the building sector in backcasting scenarios (Paper 1), energy performance metrics taking into account occupancy and use of space (Paper 3) and LCA of building components (Paper 4). The thesis also addressed the potential implementation of such assessments to set environmental performance requirements (Paper 2) or for decision support in building projects (Paper 5). Quantitative assessments of environmental performance provide a form of objective basis to compare different options. This reduces the reliance on individual judgment (Espeland & Stevens, 2008), and provides flexibility and opportunities to adapt and innovate compared to prescribing technical specifications (Häkkinen & Belloni, 2011; Meacham, 2010; Selviaridis & Wynstra, 2015)

There is a need to go beyond the rationalist view that it is sufficient to simply provide decision makers with accurate numbers. Quantitative assessments are useful and the question of their accuracy is relevant, but they need to be complemented by a qualitative understanding of the context in which these assessments are used. This is particularly important when using such assessment in policymaking, as the assessments can have far-reaching effects.

The act of quantifying something, representing it with a number, has complex implications. Espeland & Stevens (2008) draw attention to several aspects of quantification: quantification requires work, it creates new categories and changes what is measured, it elicits action and provides authority, and it is linked to aesthetic considerations related to numbers. In their words, "the real becomes coextensive with what is measurable" (Espeland & Stevens, 2008, p 432).

The thesis similarly shows how the way sustainability is quantified hides or reveals different aspects of it. Thus, the spreadsheet model used in Paper 1 enabled a concrete representation of some particular aspects of buildings in backcasting scenarios, and drew attention to sensitive parameters that are rarely discussed, such as amount of new construction and floor area per person. Since it was not comprehensive and entailed a number of arbitrary assumptions (unavoidable in such a backcasting study), the model's value was not primarily in its accuracy or predictive power, but rather in its use to support a discussion of images of the future and complement qualitative approaches to scenario development. Conversely, normalizing assessments of energy- or environmental performance based solely on floor area hides other aspects of buildings, such as how space is used (Paper 3). Therefore, the spreadsheet model in Paper 1 drew attention to an aspect that is usually made invisible by other more conventional forms of quantification.

This role of environmental performance assessments in hiding or revealing particular issues has important implications for the development and standardization of assessment and certification tools. Certification systems and databases of environmental impacts for construction products become the de facto definition of sustainability for their users, but they are based on criteria that are not immediately visible to the users (Paper 5). Rydin (2013) mentions a similar "black box" role for energy performance assessments. An important takeaway is that aspects that are not addressed by these widespread tools risk being excluded from actors' considerations altogether, possibly without the practitioners even realizing it. Such assessment tools hide the complex and multifaceted nature of sustainability, but this is necessary to make the concept actionable. Practitioners' understanding of sustainability at an operational level depends on the tools they use and the data they have access to; therefore it is important to ensure that these tools and data take into account important sustainability aspects. The recent development of a database of generic GWP data for construction materials in Sweden might help putting the issue of embodied GWP on the agenda (Swedish National Board of Housing Building and Planning, 2021). Another approach could be to integrate GWP into the grading systems of tools already used by practitioners.

Another potential effect of environmental performance assessments is the fact that they provide reference points, a common language and practical criteria allowing actors to work together on the ambiguous and contested concept of sustainability. Nicolini, Mengis, & Swan (2012) point to the key role of such boundary objects in enabling collaboration. Schröder (2018) showed how the concept of sustainability is translated at the various steps of a construction project. The thesis showed that the use of tools, databases and certification systems in Sweden plays an essential role in this translation, although in other countries this process might rely more on the agency of practitioners (Paper 5). Assessment tools, as boundary objects, might help actors discuss and take into account sustainability issues. Therefore, a widespread implementation of LCA could lead to more consideration of sustainability issues, regardless of whether LCA is actually used to inform design or enforce requirements. In green procurement, environmental performance requirements might raise awareness among suppliers and signal sustainability ambitions and expectations, even when such requirements do not weigh much in selecting alternatives (Kadefors et al., 2021; Varnäs, Balfors, & Faith-Ell, 2009). This implies that the upcoming mandatory declaration of GWP for construction projects in Sweden could improve the consideration of sustainability in the building sector, even though the declaration does not include limit values and only covers part of the life cycle. Still, the implementation of such a mandatory declaration should be monitored to ensure that it does not have unwanted consequences. If only part of the life cycle is included, could it lead to "burden shifting" towards life cycle stages that are not included? What technical definition of sustainability does it convey, what other definitions and aspects of sustainability remain hidden?

Quantitative assessments of environmental performance could be seen as mediators that do not necessarily determine building design through direct cause-and-effect relationships, but influence it by translating and shaping the meaning of sustainability. Decisions result from the interplay of these assessments with other factors, agencies and constraints. Some assessments are perhaps better understood as "qualculations", i.e.

combinations of calculations and qualitative judgments (Callon & Law, 2005; Georg & Tryggestad, 2009). Further research could build on other theories to investigate other effects of assessments that have not been addressed in this thesis. In particular, institutional theory could shed light on the attribution of legitimacy (Brunsson, 2007; March, 1994), which seems to be an important reason for using LCA, especially in certification and flagship projects.

5.3 Contribution to the field of sustainability science

This section examines the overall approach of the thesis to discuss its validity and relevance, in the context of sustainability science as discussed in section 2.1. As a whole, the thesis addresses aspects of building sustainability at multiple levels, combining insights from different paradigms, and investigates sustainability issues that are rarely in the spotlight.

In systems thinking, the concept of "leverage points" provides a framework for reflecting about what kinds of interventions are likely to trigger change in a complex system (Abson et al., 2017; Meadows, 1999). A core idea is that "deeper" leverage points are often more effective in inducing change, but also more difficult to influence (as illustrated in Figure 6). Thus, adjusting the detailed parameters of various policies and measures is thought to be less likely to lead to system change than modifying existing feedback loops in the system. Feedback loops are themselves less likely to induce change than modifications in the structures, rules and institutions governing the system, which are themselves less likely to trigger change than evolutions in the prevalent mindsets and paradigms behind these structures. Each element in this list is more effective than the last at creating system-wide changes, but is also more immutable, more difficult to steer.

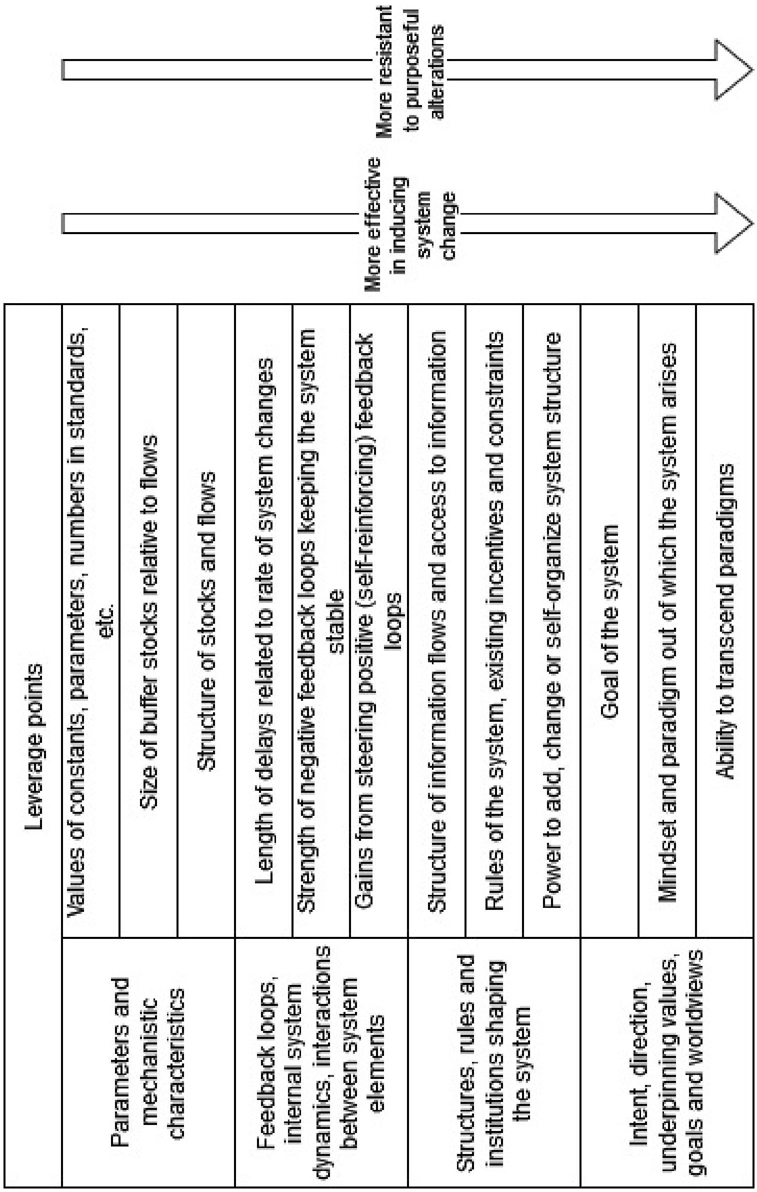


Figure 6 – The leverage points framework for system change (adapted from Abson et al., 2017 and Meadows, 1999)

The thesis addresses issues at several different levels: paradigms and strategies for the building sector as a whole (Paper 1), challenges to the implementation of new rules and structures within local public authorities (Paper 2) and companies (Papers 3 and 5), as well as detailed parameters in LCA (Paper 4) and energy performance metrics (Paper 3). The latter work with detailed parameters has tangible implications and is useful in the short term to support the development and application of LCA-based policies and tools in the building sector. The "deep level" work with scenarios challenging current paradigms in Paper 1 attempts to address a leverage point that is potentially much more impactful, but it is harder to see its direct implications. While there is a need for more research addressing deeper leverage points, research addressing e.g. technical questions related to LCA has also been needed, in a context where LCA is increasingly being used in regulation and could have far-reaching consequences on practices in the future.

Furthermore, the thesis also links different levels of the leverage points framework. "Deep level" reflections about radical scenarios for the building sector influence "shallow level" parameters. Hence, the backcasting model (Paper 1) highlighted floor area per person as an issue of interest, which led to the consideration of what energy performance metrics could be used in practice to consider the effect of occupancy and space efficiency (Paper 3). Although this has not been addressed in this thesis, policy scenarios regarding e.g. future energy supply can also influence the parameters and outcomes of assessments such as LCA. Conversely, "shallow level" issues such as technical questions regarding LCA methodology and data can have consequences at a much deeper level. Hence, changes in LCA calculation method, data sources and included life cycle stages (Paper 4) can lead to different outcomes, which can have far-reaching consequences if LCA is used to support high-level decisions. Other issues related e.g. to the modelling of electricity supply or biogenic carbon, not addressed in this thesis, also have the potential to affect strategies adopted in the building sector (extent of insulation, use of structural timber or PV panels). Similarly, the criteria used in certification systems and environmental databases for construction products can deeply affect practitioners' views of what constitutes a sustainable building (Paper 5). These examples illustrate interconnections between leverage points at different levels, and draw attention to the fact that changes in technical or numerical details can sometimes ripple and deeply affect the system.

Spangenberg (2011) provides quality criteria for research in sustainability science. Sustainability science must be purpose-bound, integrating analyses and assessments based on a variety of methods and both academic and non-academic disciplines. While “science for sustainability” is often monodisciplinary and based on traditional criteria of scientific rigor, “science of sustainability” is inter- or transdisciplinary and based on criteria of “post-normal science”, which acknowledges complexity, uncertainty, unclear or changing problem definitions and the need to produce knowledge beyond academia. The present thesis can mostly be characterized as “science for sustainability”. It is purpose-driven, aiming to create knowledge contributing to changes towards more sustainable practices. Each individual study is monodisciplinary. However, as a whole, the thesis does benefit from combining insights from multiple paradigms and disciplines. The benefits of combining multiple theoretical perspectives have been highlighted by Gioia & Pitre (1990), Lewis & Grimes (1999) and Geels (2010). Lewis & Grimes (1999) mention that paradigm diversity fosters creative insights when studying complex phenomena. They argue for the use of multiple paradigms to study a single phenomenon from different perspectives. The approach in this thesis is different, since different paradigms are used to study different phenomena. Still, combining perspectives from futures studies, actor-network theory, decision theory, and quantitative assessments of environmental impacts provides a holistic understanding of relevant aspects to promote sustainable decisions related to building design and operation.

6 Conclusions

The present thesis investigated how to support the implementation of measures to mitigate GWP in the building sector, in line with the fulfilment of climate targets. It addressed different levels, from highlighting relevant strategic issues that have not received much attention, to implementing environmental impact mitigation practices at an operational level. It focused in particular on challenges to the implementation of sustainable practices, and on the role of quantitative assessments of environmental performance in steering their adoption.

At a strategic level, the thesis exemplified how a quantitative model of buildings' GWP in backcasting scenarios could support a discussion regarding how buildings are designed and operated. In particular, it showed the necessity of mitigating embodied GWP from construction and renovation, through changes in construction materials as well as a reduction of new construction. It also highlighted floor area per person as a particularly significant parameter, indicating the relevance of space sharing and other strategies to optimize use of space. The thesis explored further some key aspects and challenges to the adoption of space sharing. There are regulatory barriers to space sharing, as regulation is sometimes unclear about the rules that apply in shared and multifunctional premises (e.g. ventilation, fire safety, rights and responsibilities of the tenants and owners, etc.). Space sharing also requires practices and service-oriented business models that consider not only the floor area of buildings, but also the ways they are used. More specifically, most metrics to assess building performance, in particular energy performance, are based only on floor area. Complementary metrics, taking into account space efficiency and occupancy, are needed in order to put on the agenda the important question of "how buildings are used".

The thesis focused further on the role of quantitative assessments of environmental performance in steering towards lower environmental impacts. One potential use case investigated was the use of environmental performance requirements by Swedish municipalities. Here too, the thesis highlighted regulatory challenges linked to ambiguities regarding what kinds of requirements can be set by Swedish municipalities. There is a need for clear guidance regarding the ways in which municipalities can steer buildings' environmental impacts, and to what extent they can set related requirements e.g. in detailed development plans. Furthermore, using LCA to set environmental performance requirements at the local level would require overcoming barriers related to high costs in terms of time and resources, as well as a lack of skill and data. Similarly, a study of design processes in housing projects showed high constraints in terms of time and costs as well as limited LCA skills. Some design choices within a project are based on standardized typologies, guidelines and default solutions. This implies that important decisions influencing the building's environmental impacts are taken upstream of the project, during the development of these guidelines. However, these constraints and standardized solutions do not fully determine the final design, as they are bent and adapted on a case-by-case basis. While there seems to be limited opportunities to use LCA as a proactive design tool within such projects, LCA could instead be used at the level of the organization, to inform the development of these guidelines and default solutions.

A more widespread use of LCA in procurement, regulation or design requires a good understanding of how choices of method and data influence LCA results. The thesis showed how differences in service life data between industry sources and a generic database could significantly change the outcome of LCA for some building elements (e.g. façades). The choice of reference study period (RSP) for the assessment also has consequences: a longer period showcases the benefits of more durable materials, while a shorter period promotes an earlier reduction of emissions and limits uncertainties related to future scenarios. Differences in calculation methods also affect the outcome. The choice between using a round-up or annualized number of replacement operations might not lead to significant differences in many cases, but it significantly affects the results in some particular cases (when an element would be replaced shortly before the end of the RSP). This indicates the importance of continuously improving the availability of accurate environmental and service life data, and of harmonizing methodological choices. This should be an ongoing process as LCA becomes more widely used, to ensure that results are comparable and do promote sustainable practices, and to facilitate the understanding and adoption of LCA by practitioners.

Furthermore, the thesis drew attention to the ways quantitative assessments hide or reveal various aspects of the complex issue of sustainability. For instance, metrics normalized per unit floor area ignore the way space is used. Similarly, standardized databases giving a single "sustainability score" create a de facto definition of sustainability based on criteria that are hidden from the users. Such simplifications and standardizations are necessary to operationalize the ambiguous and contested concept of “sustainable building” and enable cooperation. However, designers and users of such assessment tools should be aware of what aspects they include or exclude. Conversely, the use of appropriate metrics and models can support the discussion of sustainability issues by creating a common language and reference points. Often, it can be fruitful to use a combination of metrics together, such as complementing conventional energy metrics with metrics that consider occupancy and space efficiency.

Overall, the thesis addressed some understudied issues related to building sustainability. It showed the need to address challenges to environmental impact mitigation practices, related in particular to ambiguous regulations or legal constraints, limited time, knowledge and resources, and a need for standardized methods and reliable data for LCA. When resources are too limited to use LCA in every single project, LCA could instead be used to develop standardized designs to be implemented in future projects. The upcoming mandatory declaration of GWP in Sweden, the development of a generic database of climate impact for construction materials, and the ongoing integration of LCA with Building Information Modelling (BIM) tools, all contribute to bridging skill- and data gaps. A widespread implementation of LCA could also provide a boundary object to build a common understanding of sustainability, spotlight it as an important topic and make it an actionable concept. However, as this wider use of LCA is implemented, there is a need to monitor its consequences to ensure that it does steer towards lower environmental impacts (considering choices of data, assumptions and calculation methods). Moreover, as the mandatory declaration and other standardized assessments such as Miljöbyggnad focus on a single impact category (global warming potential) and a partial life cycle (e.g. cradle-to-handover), there is a need to ensure that they do not lead to burden shifting towards other impact categories and life cycle stages. The fact that the mandatory declaration of GWP in Sweden does not include limit values in the short term offers an opportunity to assess its consequences before they become binding.

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