Buildings in municipal climate change mitigation strategies: towards life cycle thinking

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SUMMARY

Fulfilling climate targets requires ambitious changes. The building sector is a large contributor to emissions of greenhouse gases (GHG), but also offers opportunities for climate change impact reductions. This thesis aims at supporting strategic decisions to reach climate change mitigation targets in the building sector, based on knowledge about what factors contribute significantly to climate impact from buildings in a life cycle perspective and how practitioners can influence these factors. More specifically, a first point of investigation concerns what aspects play a key importance in buildings' climate impact, and what climate change mitigation strategies for the building sector should focus on. A quantitative analysis of backcasting scenarios for 2050 was performed using a spreadsheet model to estimate GHG emissions for the building sector. The parameters were adjusted to ensure that a GHG emission quota was reached in every scenario. This provided an illustration of four very different ways the building sector could contribute to the fulfillment of a global climate change mitigation target. The results were used to discuss what aspects of buildings were particularly important for target fulfillment. These aspects include a low-carbon energy mix, a reduction of GHG emissions from construction materials and an optimized use of space. A second point of investigation concerns how municipalities can influence practices through the use of environmental requirements in construction, in particular requirements based on a life cycle approach. A survey of Swedish municipalities was used to assess their current practices and knowledge level regarding mitigating climate change impact from construction, as well as the influence of a municipality's size on these practices. It was followed up by semi-structured interviews investigating barriers to the use of environmental requirements in construction. Barriers were identified regarding in-house skills, access to data, resources, ambiguities regarding the law and guidance from national authorities. A stepwise strategy was suggested to overcome these barriers and successfully implement environmental requirements. Therefore, the thesis as a whole provides insight on how municipalities could use environmental requirements in construction to influence current practices in the building sector, so that the changes needed to fulfill the 1.5°C target are implemented.

SAMMANFATTNING

Ambitiösa förändringar krävs för att uppnå målet om att begränsa den globala temperaturökningen under 1.5°C. Byggsektorn bidrar mycket till globala växthusgasutsläpp, men erbjuder också möjligheter för att minska klimatpåverkan. Denna avhandling syftar till att stödja strategiska beslut för att nå klimatmålet inom byggsektorn, baserat på kunskap om vilka faktorer som bidrar mest till klimatpåverkan från byggnader i ett livscykelperspektiv och hur praktiker kan påverka dessa faktorer. Först undersöktes byggnadsaspekter som är viktiga för att nå klimatmålet och som strategier för minskad klimatpåverkan från byggnader bör fokusera på. En kvantitativ analys av backcasting-scenarier utfördes för att uppskatta växthusgasutsläpp från Sveriges byggnadsbestånd fram till, och under år 2050. Centrala parametrar justerades för att säkerställa att en målnivå för växthusgaser underskreds i varje scenario. Detta gav en illustration av fyra olika sätt som byggsektorn i Sverige kunde bidra till uppfyllandet av ett globalt klimatmål. Resultaten användes som underlag för att diskutera vilka byggnadsaspekter verkar vara särskilt viktiga för måluppfyllelse. Dessa aspekter inkluderar energiförsörjning med låga växthusgasutsläpp, en minskning av växthusgasutsläpp från byggmaterial samt yteffektivisering i lägenheter och lokaler. I en annan studie undersöktes hur kommuner kan påverka nuvarande praxis genom att ställa miljökrav vid byggandet, särskilt krav som bygger på livscykelanalys. En enkät i svenska kommuner användes för att bedöma kommunernas nuvarande praxis och kunskapsnivå när det gäller klimatpåverkan från byggandet. Enkäten följdes upp med semistrukturerade intervjuer som undersökte hinder för användningen av miljökrav i byggandet, särskilt LCA-baserade krav. Barriärer som brist på kompetens, data och resurser, tvetydigheter i lagen och bristande vägledning från nationella myndigheter identifierades. En strategi föreslås för att övervinna dessa hinder och implementera miljökrav. Som helhet ger avhandlingen inblick i hur kommunerna kan använda miljökrav vid byggandet för att påverka nuvarande praxis inom byggsektorn, så att de förändringar som krävs för att uppfylla 1.5°C-målet genomförs.

Acknowledgements

As I'm putting the final touch to this cover essay, I've been doing research at SEED for a bit over three years, first as a master student, then as a research engineer, then as a PhD student. This time has been exciting, stimulating and at times challenging, but overall it's been an amazing experience and I'm hoping it will continue this way for the years to come!

I'd like to thank Tove Malmqvist for giving me the opportunity to start this great journey in the first place, and for supervising me ever since. Tove, I'm very grateful for your advice and support! I'm also grateful for the input of my co-supervisor Martin Erlandsson. Martin, your knowledge of what is going on 'in the real world' helped me make my research more relevant.

Thank you to all my colleagues at SEED for making our department such a welcoming and stimulating place. I'm grateful to everyone who has ever shared a room, a fika or an idea with me! I wouldn't be able to do what I do without this positive atmosphere.

To all my friends and loved ones in France and in Sweden: your support and the good times we share mean the world to me. Thanks to Félix, Juliette and Rémi for making Stockholm feel a bit more like home. And thanks especially to Anna: you're the best, even though you refuse to admit it!

Nicolas Francart
Stockholm, February 2019

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Paper 2: 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

Contribution to each paper

Paper 1

I developed the spreadsheet model and performed the analysis that is the basis of paper 1. A first version of the model was developed during my master thesis. I refined and developed it further before writing paper 1. I was the main author of paper 1 and wrote most of the text. Tove Malmqvist provided feedback and revisions, and Pernilla Hagbert contributed with comments and text for the introduction, discussion and conclusion.

Paper 2

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. Josefin Florell was not involved in writing the article. I therefore worked with exploiting the interview results based on transcripts. I was the main author of paper 2. Mathias Larsson contributed with early versions of the text about interviews. Tove Malmqvist and Martin Erlandsson provided feedback and revisions.

1 Introduction

1.1 The role of municipalities in mitigating buildings' climate change impact

1.1.1 Buildings' climate change impact

There is now widespread consensus in the scientific community that average global temperature is rising and that human activity is extremely likely to be the main driver of this change (Foster & Rahmstorf, 2011; Haustein et al., 2017; Kirtman, Adedoyin, & Bindoff, 2013; Leach et al., 2018). Climate change is not the only environmental sustainability issue, but it is an issue of core importance for the integrity of the Earth system (Steffen et al., 2015). Climate change has been the focus of many research projects and policy initiatives, in particular in Sweden, due to its environmental relevance and the fact that it can be linked to quantitative indicators that are relevant for national policies and industrial practices.

In this context, it is of particular relevance to focus on the impact of buildings in a life cycle perspective, for three reasons. The first is that the share of total greenhouse gases (GHG) emissions attributed to the construction sector (including buildings and infrastructure) has been estimated to be around 16% within the EU (Eurostat, 2018), and up to 40% in e.g. China (Yokoo, Oka, Yokoyama, Sawachi, & Yamamoto, 2015). As buildings become more and more energy efficient and the energy supply becomes less carbon-intensive, reducing the impact of the construction of buildings becomes an issue of comparable importance with reducing operational energy use (Anand & Amor, 2017; Birgisdottir et al., 2017; Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013; Liljenström et al., 2015).

The second reason to consider the impact of buildings is that many countries experience quick and extensive urbanization (United Nations Department of Economic and Social Affairs Population Division, 2014). Sweden, which will be the focus of this licentiate thesis, experiences high population growth in cities, and the demand for new housing in urban areas leads to much new construction. There is therefore a risk for major environmental damage if the impact of new buildings is not limited.

The third reason is that there is significant potential to reduce GHG emissions caused by the construction and operation of buildings. Energy efficiency measures (e.g. thermal insulation) help reduce the impact of operational energy use. Emissions from construction materials can be reduced e.g. by increasing the use of timber and straw bale for building frames and insulation respectively (Peñaloza, Erlandsson, & Falk, 2016), by reusing construction materials or using concrete with fly ash or a lower clinker content (Razi, Razak, & Khalid, 2016). The way a building is designed also affects its climate change impact. Space can be shared, optimized and used more intensively, decreasing the floor area needed for each activity (Sekki, Airaksinen, & Saari, 2015). The shape of a building and aspects such as ceiling height and the size of windows can impact emissions from construction, operation but also indoor environment quality.

1.1.2 The role of Swedish municipalities

The climate change impact of buildings can be dealt with at different scales. The present licentiate thesis includes a study dealing specifically with guidance for municipalities to facilitate the implementation of environmental requirements in construction (Paper 2). It was performed as part of the "Toolbox for market implementation of LCA in building construction"[1] research program (in short, Toolbox program), which aims at promoting the use of life cycle assessment (LCA) to support decisions in procurement for construction projects.

Swedish municipalities are local administrative units. They show high levels of ambition for climate change mitigation, and most of them have established local plans in that regard (Fenton, Gustafsson, Ivner, & Palm, 2015; Reckien et al., 2018; Wretling, Gunnarsson-Östling, Hörnberg, & Balfors, 2018). Because they are more responsive and have a better knowledge of the local situation than national actors, local authorities can play a decisive role in climate change mitigation strategies (Brilhante & Skinner, 2015).

Municipalities are relevant when discussing climate change impact from buildings, for two main reasons. First, the role of Swedish municipalities as defined by the Municipal Law (2017:725) entails, among other aspects,

[1] https://www.e2b2.se/forskningsprojekt-i-e2b2/material/verktygslaada-foer-livscykelanalys-i-byggandet/

responsibility over all steps of the physical planning process, including:

- Visions and comprehensive plans setting long term strategies for municipal development

- Detailed plans regulating development in specific areas

- Land allocation and land exploitation agreements, specifying how the detailed plan will be implemented on a parcel of land that is owned by the municipality or by a private owner, respectively.

- Building permits, issued to developers if they respect the Planning and Building Act (SFS 2010:900) and the building code (BFS 2017:5).

It has been argued that planning has a key role to play, both in reducing GHG emissions and in making cities resilient to the consequences of climate change (Bulkeley, Castán Broto, Hodson, & Marvin, 2011).

Second, in their role as property owners, municipalities commission large construction projects for public buildings such as schools, and are major actors in procurement. Green public procurement (GPP) is recognized by the European Commission as an important strategy to reach sustainability targets. Public procurement amounts to an estimated 14% of EU GDP, and public authorities such as municipalities can use this purchasing power as a lever to promote sustainability innovations and create demand for sustainable products (European Commission, 2016a). Construction is highlighted as a sector where GPP can be particularly influential due to the large share of public purchasers in the market. Because of their constant interaction with building industry stakeholders, municipalities also have an opportunity to disseminate knowledge and initiate dialogues about sustainability issues.

1.2 Global, national and local targets for climate change mitigation

The first section addressed the importance of mitigating climate change impacts, in particular from buildings, and highlighted municipalities as key actors for mitigation strategies. This section will address targets for climate change mitigation at various levels.

At the international level, the most recent and prominent target agreed upon can be found in the Paris agreement (United Nations Framework Convention on Climate Change, 2015) and corresponds to a limitation of global average temperature increase "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". It has been argued that this global average temperature target lacks a solid scientific basis supporting it as an optimal value, but that it is nonetheless useful as a focal point to communicate, coordinate multiple actors and strike agreements to stabilize global average temperature in the long term (Jaeger & Jaeger, 2011). To be useful for practitioners, this target must be translated into indicators that are more actionable at a national and local level.

In targets for individual countries or groups of countries, climate change mitigation is often formulated in terms of GHG emissions at a specific year. For instance, the EU "Roadmap for moving to a competitive low carbon economy in 2050" aims for a reduction of GHG emissions of 80-95% in 2050 compared to 1990 (European Commission, 2011). Sweden's climate policy framework aims at reducing GHG emissions by 63% by 2030 (compared to 1990), 75% by 2040, reaching net zero emissions by 2045 and thereafter achieving negative GHG emissions. Negative GHG emissions include carbon capture and storage, uptake from biomass and investments in climate-friendly projects abroad (Government Offices of Sweden, 2018). In addition to GHG emissions occurring on the Swedish territory, GHG emissions caused by Swedish consumption in and outside of Sweden are also monitored.

At the municipal level, climate change is an issue that has been addressed more and more in Sweden during the last decade, and many municipalities have a plan with an explicit target to decrease GHG emissions (Wretling et al., 2018). Local targets can take different forms: they vary in their scope (geographic area, time horizon, activities included), their indicator (GHG emissions, energy use, etc.) and their perspective (emissions from consumption or production, life cycle perspective or not) (Kramers et al., 2013). Although production-based targets are used in most cases, some municipalities such as Gothenburg have targets to reduce GHG emissions both in a production and in a consumption perspective (City of Gothenburg, 2014).

Scaling down even more, requirements and certification schemes at the building level often include criteria relevant to the climate issue, along with other environmental and health criteria. Certification schemes such as LEED (United States Green Building Council, 2018), BREEAM (Building Research Establishment, 2018) and Miljöbyggnad (Swedish Green Building Council, 2017) include criteria on e.g. thermal insulation, material inventories, material waste or renewable energy use (depending on the scheme). Climate targets are thus translated into criteria that are directly actionable for practitioners who wish to certify a building. Often, these criteria are formulated as actions that must be taken in order for the building to be certified, such as "implementing a procedure for construction waste management". Many criteria concern the provision of information, such as "providing a logbook of all construction materials used". Some criteria can also be based on performance indicators, such as "reducing climate change impact from materials in a life cycle perspective under a certain threshold". A certification scheme called NollCO2, based on direct calculations of GHG emissions for the entire building in a life cycle perspective, is currently in pilot phase (Sweden Green Building Council, 2018). The Swedish National Board of Housing, Building and Planning (Boverket) has also proposed that climate change impact from construction materials and processes should be calculated for all new buildings (Swedish National Board of Housing Building and Planning, 2018).

1.3 Moving from setting targets to implementing measures

The previous section reviewed various ways of expressing targets for climate change mitigation, and how these translate into local targets and building criteria. This section will address the issue of reaching these targets and meeting these criteria in practice. How can we move from setting a target to guiding decisions and implementing suitable actions to reach it?

In this licentiate thesis, I focus on two particular aspects of sustainability strategies: First, I consider how futures studies can be used to inform current decisions. Then, I consider the necessity to overcome barriers to implementation and bridge the gap between theoretical strategies and actual practice.

1.3.1 Future scenarios for decision support

Reaching an ambitious climate target requires comprehensive, well-planned and coordinated measures. Models and future scenarios can be used to discuss possible strategies to reach sustainability targets and support policymaking (van Dorsser, Walker, Taneja, & Marchau, 2018). Future scenarios can inform current practices by contributing to the discussion of alternatives, opening up new perspectives or providing recommendations (e.g. “To reach this target, the following aspects appear to be critical and a possible strategy to address them is…”). They can allow a shift from discourses of continuous incremental improvement (e.g. “This building’s environmental performance is better than average, therefore it is good enough”) to more target-focused discussions of what is actually needed to reach the target (e.g. “This building’s environmental performance may be better than average, but we need to do better if we want to reach the target”). Scenarios can also be integrated with other methods to assess environmental performance, such as life cycle assessment (LCA, e.g. “Assuming the following future electricity mix, the environmental impact of operational energy use in this building will be…”).

Scenarios differ based e.g. on their geographical scope (the European energy market, the Nordic grid, the Swedish energy market), their conceptual scope (a focus on a specific sector, e.g. energy, or a more overarching scope) and on the assumptions taken regarding future development (straight projections of current trends, forecasts based on assumptions or explorative scenarios detached from current trends). These aspects influence the kind of recommendation given when using scenarios to inform current decisions, and should therefore be carefully considered.

An example of scenarios relevant for the climate issues can be found in the IPCC report “Global warming of 1.5°C”, which includes models of various pathways for the fulfillment of the 1.5°C target. Pathways limiting warming to 1.5°C without overshoot show more ambitious reductions in GHG emissions than agreed in the Paris Agreement, with emission reductions of 40-60% between 2010 and 2030 and net zero emissions shortly after 2050 (Intergovernmental Panel on Climate Change, 2018c, section C.1). Moreover, all but one pathways rely on carbon dioxide removal technologies, in particular bioenergy coupled with carbon capture and storage (BECCS). Carbon dioxide removal technologies have controversial implications for environmental sustainability, due to e.g. land use and competition with agricultural land for afforestation and bioenergy, a lack of economic incentives, and concerns about the feasibility of upscaling (Intergovernmental Panel on Climate Change, 2018b, see section 4.3.7). The scenario that does not rely on BECCS assumes more ambitious changes in terms of technology, land use and consumption patterns, e.g. for goods and energy. Insights for current policies can be gained from these scenarios: for instance, it appears that current pledges for GHG emissions reduction are insufficient, that carbon removal technologies must be an important question on the agenda, and that changes in consumption patterns will be needed unless carbon removal is very extensive. This is an example of how scenarios can provide input to develop sustainability strategies.

Other scenarios relevant for the climate issue can be found in the Beyond GDP Growth research program[2]. Contrary to the IPCC scenarios and many other projects, it investigated scenarios to reach the 1.5°C target that don't rely on economic growth or carbon dioxide removal. It covered 4 scenarios to reach sustainability targets by radically breaking with current trends in very different ways (including high technology and full automation, local decentralized self-sufficient communities, high-efficiency circular economy and sharing-based lifestyles). The present licentiate thesis includes work performed as part of the Beyond GDP Growth research program, modeling what it would entail for buildings to reach the climate target in each of the scenarios (Paper 1). One purpose of the program has been to use scenarios to support policymakers. In particular, a number of municipalities were partners of the project and interested in insights that could be gained for their practices.

There are plenty of other examples of futures scenarios that can support current decisions or help develop climate change mitigation strategies. Some examples related to buildings and energy supply and relevant for Sweden include:

- Scenarios on Sweden's energy system (Swedish Energy Agency, 2017), including a predictive reference scenario and two alternative scenarios regarding likely developments in energy supply and demand. This is part of Sweden's official reporting on GHG emissions to the European Commission.

[2] http://www.bortombnptillvaxt.se/

• The EU Reference Scenario on energy, transport and GHG emissions (European Commission, 2016b), based on projections of current policies and trends.

• Four Futures (Fyra Framtider) (Swedish Energy Agency, 2016), a set of explorative scenarios developed by the Swedish Energy Agency to discuss various possibilities regarding the future of energy supply and demand in Sweden.

• Nordic Energy Technology Perspectives (NETP) (International Energy Agency, 2016), a case study investigating pathways for low-carbon energy in the Nordic countries, with a strong focus on decision support for policymakers and practitioners.

• North European Energy Perspectives Project (NEPP) (Rydén & Unger, 2018), a collaboration between academia and private sector practitioners focusing on concrete and technical aspects of the energy system and success factors to meet the objectives of both politicians and practitioners.

1.3.2 A gap between theory and practice

Future scenarios are one way to discuss how a climate target could be reached in theory. However, there is a need to bridge the gap between long-term strategic thinking that is mostly theoretical, and practical implementation of measures today. In the case of buildings, one way to impact current practices is to set environmental criteria e.g. in procurement processes, in certification schemes or in municipal development plans. Such criteria can prescribe specific measures, such as forbidding the use of certain construction materials. Prescriptive criteria are simple to implement and monitor, but they risk hindering competition and innovation and leading to sub-optimal designs (Meacham, 2010; Selviaridis & Wynstra, 2015). Another type of criteria can be based on setting a threshold for a relevant indicator of environmental performance, such as GHG emissions calculated with an LCA approach.

Awareness about LCA has increased in the building sector, but its adoption is limited by the need for time, training and investments, the difficulty to access appropriate data, a lack of standardization and transparency limiting comparability and concerns over validity of the results (Brick, 2008; Rønning & Brekke, 2014; Schlanbusch et al., 2016). It has also been pointed out that the methodology, metrics, system boundaries and aim of LCA can be incompatible with other decision support tools (Dong et al., 2018). Similar issues exist for other methods, in other contexts. At the municipal level, work with energy and climate strategies is often limited by a lack of resources and by the legal context surrounding municipal planning (Wretling et al., 2018). In green public procurement (GPP), studies indicate that the main barriers to sustainable decisions are the strategy, culture and management practices of an organization, and in particular economic preoccupations (Appolloni, Sun, Jia, & Li, 2014).

Therefore, there are practical barriers to the implementation of optimal sustainable choices for buildings in various contexts. Even if there are available methods to theoretically inform practitioners about how to improve the environmental performance of buildings, there is a need to understand and overcome practical barriers to have an actual impact on practices in the building sector.

1.4 Aim of the licentiate thesis

The overarching aim of this thesis is to support strategic decisions to reach climate change mitigation targets in the building sector, based on knowledge about what factors contribute significantly to climate change impact from buildings in a life cycle perspective and how practitioners can influence these factors. More specifically, I focus on two aspects of this issue. The first is picturing what it could entail for the built environment to be compatible with climate change mitigation targets: there is a known destination, but many ways to get there. The second is investigating how to implement best practices today through the use of requirements: there is a gap to bridge between choosing in which direction to go and actually taking the first steps. The following research questions are addressed:

RQ1. What aspects of building design, construction, operation and energy supply must be addressed in order to decrease GHG emissions from Swedish buildings in line with climate change mitigation targets aiming at keeping global warming below +1.5°C?

RQ2. What are the main barriers to the use of requirements by municipalities to foster building construction with low climate change impact, in procurement and as public authorities?

RQ1 is mostly addressed in Paper 1, by using quantitative climate impact estimations in a backcasting study to support discussion about key issues and strategies for the built environment. RQ2 is mostly addressed in Paper 2, by using a survey- and interview study to investigate current practices and barriers in relation to municipalities' use of requirements to limit climate change impact from buildings. The thesis also includes a discussion of strategies that could be used to overcome barriers to the use of environmental requirements and support changes in the building sector to fulfill climate change mitigation targets.

2 Research context

This section provides background related to the concepts addressed in the licentiate thesis, and situates the research work in relation to various research fields.

2.1 LCA in the building sector

Life cycle assessment (LCA) is a method for assessing environmental and social impacts occurring throughout the life cycle of a product or service, i.e. from the acquisition of natural resources through production and use to disposal and waste management. Unless indicated otherwise, LCA in this licentiate thesis refers to process LCA, a bottom-up approach calculating impacts based on all processes occurring during the product's life cycle (as opposed to input-output LCA, a top-down approach based on transactions between industrial sectors). LCA applied to buildings arose in the 1980s, but the general methodological framework was standardized in the 1990s (with the ISO 14040 standard in 1997). Interest in LCA has risen since the 2000s, and methods and standards for the LCA of buildings have been developed (Buyle, Braet, & Audenaert, 2013). In Sweden, this includes tools such as EcoEffect and Environmental Load Profile (Forsberg & von Malmborg, 2004).

An LCA study usually comprises four phases (Finnveden & Potting, 2014):

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 function fulfilled by the system, defined by a functional unit such as "1m2 of office space to be used during 50 years". The

initial phase also includes the selection of environmental and/or social indicators 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 impacts on the chosen indicators.

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

Reviews have shown that building LCA has a number of particularities that make it considerably more complex than for many other products (Anand & Amor, 2017; Buyle et al., 2013; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014):

- There is no obvious suitable functional unit for buildings. Assessments have been performed based on e.g. heated floor area, heated volume, number of users or activity in the building. Due to the unique character of each building and differences in layout, location, comfort levels and regulations, defining a functional unit to compare different buildings is problematic.

- Assumptions have to be taken regarding the building's life span. Buildings have much longer and more uncertain life spans than most products, but individual components must be replaced or repaired throughout this life span. This entails assumptions regarding the extent and frequency of maintenance and replacements of building components and regarding future scenarios, e.g. how energy will be supplied to the building decades from now.

- The inventory phase can be particularly complex due to the large variety of materials used in construction. Data are often missing or unreliable.

- Assessment methods are not fully standardized, which makes it difficult to compare results from studies performed using different approaches. For instance, there are different ways of accounting for the environmental impact of recycled materials (should they be a non-polluting resource in the construction phase, bear part of the original material's environmental impact, or provide benefits during the end of life phase?). The timing of emissions also matters due to temporary carbon storage in timber and the carbonatization of concrete

(Brandão et al., 2013), but timing issues are often ignored in building LCA. There are also disagreements regarding what scenarios should be used for e.g. renovation or future energy supply. For instance, should the future energy mix be the same as today, based on a projection of current trends, or based on an optimistic scenario?

Estimated environmental impacts for buildings can be sensitive to the aspects mentioned above, which can impact the recommendations given. Huijbregts, Gilijamse, Ragas, & Reijnders (2003) thus point out the importance of understanding the influence of uncertainty caused by the parameters (inventory and environmental data), the scenarios (refurbishment, energy, end of life) and the model (assumptions and methodology).

Many LCA-based tools have been developed over the years, e.g. to compare construction products or perform LCI and LCIA at the building level. A review of some of these tools can be found in Cabeza, Rincón, Vilariño, Pérez, & Castell (2014). LCA can be used e.g. by urban designers, developers, architects and engineers at various stages of a construction project (Zabalza Bribián, Aranda Usón, & Scarpellini, 2009). LCA can for instance be used as a design tool together with building information modeling (BIM) to estimate and address in advance the main hotspots of environmental impacts. However, such practice is not broadly adopted due to e.g. lack of expertise and limited interest from developers (Anand & Amor, 2017; Malmqvist et al., 2011). LCA can also be used in green building certification. Certification schemes such as LEED and BREEAM offer extra credits for carrying out an LCA. The DGNB system used in Germany and Denmark awards points for using LCA in early planning phases, comparing alternatives with LCA and reaching climate neutrality in the construction and/or operation phases (German Sustainable Building Council, 2018). LCA integration in certification is however a recent trend (Anand & Amor, 2017).

Operational energy use has often been cited as the main contributor to building climate change impact. However, as operational energy performance improves and the energy supply becomes less carbon-intensive, the impact of construction materials increases comparatively to the impact of operational energy use (Anand & Amor, 2017; Buyle et al., 2013). Recent studies thus show that the construction phase can represent

50% of climate change impact for a new energy efficient building in Sweden, depending on assumptions about life span and energy supply (Birgisdóttir et al., 2016; Erlandsson, Malmqvist, Francart, & Kellner, 2018; Liljenström et al., 2015).

The present licentiate thesis does not include an LCA study per se. However, it relates closely to LCA. The modeling work performed as part of the Beyond GDP Growth research program entailed a calculation of GHG emissions from buildings in 2050 in various scenarios, based to a large extent on process LCA data. The study performed as part of the "Toolbox for market implementation of LCA in building construction" program considered instead the point of view of municipal practitioners, and dealt with practical issues related to the use of LCA tools in environmental performance requirements, such as knowledge and data gaps.

2.2 Futures studies

The denomination "futures studies" includes a range of methods and approaches to study future situations that are possible, probable or preferable (Bell, 2003). Modern Western futures studies emerged in the mid-20th century in the context of the Cold War (Son, 2015). Initially, the main topic was positivist forecasting based on trends analysis, mathematical models and analogies, with a focus on technological, economic and military issues (developed e.g. at the RAND think tank in the U.S.A).

In the late-20th century, topics related to global sustainability arose within futures studies, with the notable publication of The Limits to Growth, modeling scenarios for global-scale economic and environmental issues (Meadows, Meadows, Randers, & Behrens, 1972). This period also saw a rise in futures studies within the private sector, aimed at improving organizational strategy.

The 1990s and early 2000s saw a rise in profitability-oriented futures studies informing policy and business decisions, along with a rise in critical futures studies focused on questioning current institutions and power structures rather than reinforcing them (Schultz, 2015; Son, 2015). This fragmentation was accompanied by a broadening of the range of methods used in futures studies. Besides deterministic modeling approaches, alternative approaches appeared based on e.g. participatory processes or critical-postmodern views questioning the context in which futures studies are carried out and the values they carry (Gidley, Fien, Smith, Thomsen, & Smith, 2009). Futures studies are therefore characterized by methodological pluralism, and a multiplicity of goals, approaches and ways of knowing (Bengston, Kubik, & Bishop, 2012).

Börjeson, Höjer, Dreborg, Ekvall, & Finnveden (2006) developed one of many typologies of futures studies. They 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).

The present licentiate thesis is concerned with the fulfillment of climate change targets. Incremental changes to existing systems appear to be insufficient to reach e.g. the 1.5°C target. When the long-term target is perceived as important and reaching it can entail measures that are not profitable in the short term, it can be appropriate to perform a normative transforming study (Börjeson et al., 2006).

The present licentiate thesis contributed to the Beyond GDP Growth program, which is based on a backcasting approach. Backcasting involves developing various visions of how a target or set of targets could be fulfilled in the future. These visions can explicitly break with current trends and may well be unlikely. One can then work backwards from these desirable future states to inform current practices. Backcasting is useful to deal with complex, long term issues where current trends and intentions are part of the problem. It is used to spark ideas, broaden perspectives and envision solutions that could appear unfeasible in the light of current trends (Dreborg, 1996).

This licentiate thesis does not deal with setting the future targets to be reached; such targets are taken for granted. It does not either deal with the initial process of developing visions of the future. However, the modeling exercise I carried out can help refining and better understanding each scenario, and contributed to discussing insights gained from the scenarios for practitioners.

2.3 Climate change mitigation at the municipal level

Municipalities in Sweden work with climate change mitigation in various ways, including energy planning, physical planning and green public procurement. The supply, distribution and use of energy within the municipality are described in a strategic energy plan according to the Act on Municipal Energy Planning (1977:439). The strategic energy plan serves as reference for all energy-related decisions taken by practitioners. Land use, spatial development and physical planning are described in a comprehensive plan which details the long-term development strategy of the municipality. The implementation of this long-term strategy in each area of the municipality is ensured by legally-binding detailed plans. Developers must sign a land exploitation or land allocation agreement with the municipality, describing how the detailed plan will be implemented on each parcel of land that they own or lease from the municipality respectively. Each construction project must also be granted a building permit to ensure that they respect requirements on construction. The municipality's work with physical planning is regulated in the Planning and Building Act (SFS 2010:900), and building permits must enforce the building code (BFS 2017:5). Finally, the municipality can create demand for environmentally-friendly buildings through procurement and its own construction projects.

Sustainability concerns related to these various roles of municipalities have been the object of scientific studies in distinct but related fields. Urban design is about the layout and form of urban spaces (such as architecture guidelines for neighborhoods or the shape of streets and parks). Urban planning deals with issues related to plans and policymaking (such as infrastructure planning, development strategies and land use plans). Green public procurement (GPP) relates to public authorities seeking to buy goods and services with low environmental impact.

Altogether, these fields constitute a growing body of knowledge about how municipal practitioners can or should work with climate change mitigation. Sustainable design theorists have worked on natural resource management and design principles and architectural guidelines for sustainability at the building, neighborhood, city and region scales (Carmona, 2009).

Early sustainable urban planning studies dealt mostly with risk assessment and mono-dimensional policy studies regarding the links between urbanization and climate change (e.g. heat islands) (Jiang, Hou, Shi, & Gui, 2017). In 2007, the fourth IPCC report suggested that climate change research at the city level was an important issue. Perhaps as a result of this declaration, the number of publications in the field of sustainable urban planning rose sharply after 2007. The main research focus also changed to include multi-dimensional studies of causes and consequences of global warming for cities, governance across multiple spatial scales, issues of adaptation, resilience and social sustainability (Jiang et al., 2017).

Regarding GPP, the greening of supply chains in companies has been extensively studied but interest in environmental criteria for procurement in the public sector is more recent (Nissinen, Parikka-Alhola, & Rita, 2009). In particular, municipalities play a key role in GPP as they represent about half of governmental spending, but their practices have only been investigated in recent years (Michelsen & de Boer, 2009). However, GPP has become a subject of major interest in the EU (European Commission, 2016a) and within the scientific community, with an ever-increasing amount of yearly publications on the topic. Overall, it appears that there has been a rise in interest regarding the various ways in which local public authorities can work with climate change mitigation.

Despite this rise in sustainability concerns, practitioners have not succeeded in mitigating climate change. In Campbell (2006), Bulkeley mentions an implementation deficit in sustainable planning, claiming that climate change has been part of policies for a long time, but that it never lead to concrete changes. Planners must simultaneously adopt a longer time horizon and work to implement immediate measures. The reality of practice might also differ from the researchers' view: Säynäjoki, Heinonen, & Junnila (2014), in a focus group study, showed that municipal planners themselves consider that urban planning is unable to support broad issues of environmental sustainability, besides issues linked to housing and daily commutes. They believe that environmental sustainability is too complex to be handled at the local level and are subject to conflicting economic drivers. Carmona (2009) mentions that environmental concerns have been present in urban design theory for some time, but often absent in practice, set aside for economic reasons, or present only as "token measures" that are symbolic but have little impact. He identifies several barriers to sustainable urban design, including established patterns of living, public aspiration to consumerist lifestyles, economic and governance systems, a lack of political will, skills and visions, and the scale of the problem that makes individual contributions appear to be insignificant. Barriers related to the cost of environmental measures and the lack of resources of local authorities are also commonly mentioned regarding GPP in municipalities (Appolloni et al., 2014), and the overall effectiveness of GPP as a means to reduce environmental impacts has been questioned (Lundberg, Marklund, & Strömbäck, 2016).

Therefore, there are still significant practical gaps that must be dealt with regarding local authorities' work with climate change mitigation, either because recommended practices in strategic plans or theoretical studies are not implemented in practice, or because the measures implemented actually provide little benefits.

The present licentiate thesis addresses climate change mitigation in municipalities in two ways. The first research question relates to aspects of building design, construction and operation that are important to address to fulfill climate targets. As such, it provides insight for sustainable design at the building level and environmental strategies at the municipal level. The second research question relates to the use of environmental requirements in construction by municipalities. As such, it addresses the implementation gap between sustainable urban planning principles and practice, and the barriers and opportunities faced by practitioners to implement these principles.

3 Research design

The present research work was carried out mainly in the context of two different research programs, called "Beyond GDP Growth" and "Toolbox for market implementation of LCA in building construction" (in short, Toolbox program). Each study has therefore been carried out in a different context, using different methods. This section provides a description of each research program and highlights the methods used in each paper.

3.1 Modeling work within the Beyond GDP Growth program

3.1.1 The Beyond GDP Growth program

The Beyond GDP Growth research program[3] was initiated in 2014 and explores opportunities and challenges for fulfilling far-reaching environmental and social sustainability targets in Sweden in 2050, in a future where GDP growth is not taken for granted (Gunnarsson-Östling et al., 2017). Specifically, the targets considered were:

• An equal distribution of power

• A fair and sufficient access to resources and welfare

• GHG emissions from Swedish consumption should be compatible with the limitation of global average temperature increase under 1.5°C. This was estimated to correspond to an emission level of 820 kgCO2e/person.year in 2050, based on population projections and IPCC global scenarios limiting global warming under 1.5°C with a 50% certainty (Fauré, Svenfelt, Finnveden, & Hornborg, 2016). This corresponds to a 92% decrease compared to present emission values.

• Land use for final consumption must not overshoot global biocapacity. This means land use must be kept under 1,24 hectares per capita (Fauré et al., 2016).

In order to investigate different strategies for the fulfillment of these targets, four backcasting scenarios were developed (Gunnarsson-Östling et al., 2017):

• Circular economy in the welfare state, based on a service-oriented economy and a strong increase in material efficiency. Activity is centralized and energy and material flows function in closed loops as much as possible.

• Automation for quality of life, based on omnipresent technology. Efficiency is high due to optimal operation of most processes. After an initial investment, consumption is voluntarily limited and automation drastically decreases paid work.

• Local self-sufficiency, based on relocalization and reruralization. Society is organized in local communities, with a focus on providing food and goods to the community and lower levels of

[3] http://www.bortombnptillvaxt.se/

technology and consumption than other scenarios.

• Collaborative economy, based on the sharing of space, goods and services (including sharing vehicles, knowledge, homes, appliances, etc). Society revolves around cohousing clusters in small- to medium-sized towns.

It was decided not to discuss carbon capture and storage (CCS) in any scenario, because this technological solution has limited public acceptance and an uncertain potential for upscaling, and Sweden's environmental objectives at the time did not mention CCS. However, it should be noted that the current climate law was adopted during the project, and explicitly mentions that a share of the mitigation potential could be reached by using CCS (Government Offices of Sweden, 2018).

3.1.2 Overview of the modeling study

My work within the Beyond GDP Growth program addressed the first research question in this thesis. It consisted of an investigation of what fulfilling the climate target could entail for buildings in each scenario. Backcasting scenarios had been developed mainly in qualitative ways, and the idea was to use quantitative estimation to bring a new perspective to the discussion.

A spreadsheet model estimating GHG emissions from buildings was developed. Simultaneously, scenario descriptions from Gunnarsson-Östling et al. (2017) were used to describe what each scenario could entail for building aspects such as construction materials, energy efficiency, use of space, etc. The model was run for each scenario, adjusting parameters so that emissions in each scenario all fit under the same emission quota in 2050. The results were then discussed regarding what aspects of building design, construction and operation appeared particularly important to fulfill the GHG emission target in the building sector, what it could entail to reach the emission target, and what potential conflicts or synergies between sustainable building practices must be addressed. This led to the publication of Paper 1.

3.1.3 Quantitative analysis in backcasting

Quantitative analysis has been used in backcasting studies to develop or assess scenarios, and to specify pathways towards goal fulfillment. Several backcasting studies have quantified levels of GHG emissions or energy use, for buildings or society as a whole. They differ in several aspects:

• Their conceptual scope. The present project focused on the building sector, although the Beyond GDP Growth program had a broader scope. Some studies use overarching input-output models of material and energy flows at societal level (Fujino et al., 2008) or broad indicators of changes in behaviors, industrial activity, energy supply, etc in each scenario (Åkerman, Isaksson, Johansson, & Hedberg, 2007). Other focus on developing scenarios for a much narrower property, such as heating in buildings (Doyle & Davies, 2013).

• Their temporal scope. The Beyond GDP Growth program focused on developing images of the future in 2050. Other studies focus instead on developing and quantifying roadmaps, exploring pathways and strategies to bridge the current situation and a future target (Ashina et al., 2010; Svenfelt, Engstrom, & Svane, 2011).

• Their ambition level. The Beyond GDP Growth program adopted very ambitious sustainability targets (the climate target entails for instance a 92% reduction in GHG emissions from Swedish consumption), and the scenarios developed were all based on changes in current paradigms (some more radical than others). No study found during the literature review had a more ambitious climate target, and some had considerably lower ambition levels and scenarios that were closer to current paradigms (e.g. a 45% reduction in GHG emissions in Gomi, Ochi, & Matsuoka (2011)).

The present study focusing on the climate change impact of buildings appeared to be unique in two ways. First, it considers GHG emissions at the target year together with operational energy use and cumulative embodied emissions before the target year, and investigates tradeoffs between these aspects. Second, the scenarios appear to be more detached from current paradigms than other similar studies. No other study reviewed assumed for instance hypotheses of zero economic growth and zero nuclear power production.

Making quantitative assessments in that context gives rise to a number of methodological issues. Most of these issues relate to uncertainties inherent to future studies, for instance uncertainties about possible technological development in the future. These issues are further exacerbated in a backcasting study, because the point of the study is precisely to break from current trends.

Contrary to forecasting studies, it is then irrelevant to make assumptions on e.g. future levels of energy efficiency or available technologies based on past trends. When working with scenarios that are radically different from the present and from each other, the assumptions taken in that regard can hardly be more than educated guesses based on future prospects for e.g. construction materials or electricity production. Making such assumptions is however less problematic in this kind of backcasting study. Indeed, the point is not to predict how buildings will look like in the future. Rather, the idea is to illustrate what it could entail for buildings to reach the target in each scenario and highlight measures that would be impactful, without focusing on whether they would be economically feasible.

3.1.4 Building a spreadsheet model as a tool for discussion

A spreadsheet model was built that estimates GHG emissions and operational energy use from buildings in 2050 (including e.g. heating, electricity use, new construction and renovation of houses, apartments and workplaces) as well as cumulative embodied GHG emissions from investments in buildings prior to 2050. The model was based on a bottom-up approach and process LCA data, estimating separately e.g. operational energy use, emissions from the construction of new buildings, emissions from renovation processes, etc. This allowed investigating aspects related to building design and construction materials in detail, which was useful to discuss the concrete implications of each scenario for buildings. The downside is that, contrary to a top-down approach based on input-output accounting of material and energy flows, this approach does not necessarily yield a good estimation of the total impact of buildings. In other words, estimating and summing together impacts from different buildings and processes with a bottom-up approach might lead to some processes being omitted, which is impossible when using an approach based on accounting for all inputs and outputs at a sector level.

Because of this choice of approach, the model had a scope of its own and its results could not be compared with other studies of GHG emissions from the built environment, often based on input-output analysis. Important parts of the built environment such as infrastructure were omitted from the model, while others such as workplaces were very simplified. It was only valid to compare an output of the model with another output of the same model, because this would guarantee that both results were based on the same methodological choices and system boundaries. This is of course problematic when trying to come up with results that must be placed in a broader context, but the point of the study was to compare aspects of different scenarios with each other as a basis for discussion. The comparisons were therefore self-contained.

The model uses about 70 parameters. Describing it in its entirety would take a considerable amount of time and space, but the reader can refer to the online supplementary material of paper 1 for more information[4]. Broadly speaking, its structure can be described by the following equation:

$$E_{buildings} = E_{heating} + E_{electricity} + E_{construction} + E_{renovation}$$

where $E_{buildings}$ is the total GHG emissions from buildings, $E_{heating}$ the emissions from operational energy use for heating, $E_{electricity}$ the emissions from operational electricity use excluding electricity for heating, $E_{construction}$ the emissions from the construction of new buildings and $E_{renovation}$ the emissions from the renovation of the existing building stock. In addition, the model also calculates operational energy use and cumulative embodied emissions from the construction and renovation of buildings and power plants prior to 2050.

The model was run with parameters reflecting the current situation, and the emission target to reach in each scenario was set at 8% of this estimated present value, to reflect the 92% decrease in GHG emissions in all scenarios. This yielded a quota of 100 kgCO2e/person.year within the boundaries of the model. The parameters of the model were then adjusted for each scenario, based on two criteria:

• The parameter values should illustrate the scenarios and be consistent with scenario descriptions previously developed in Gunnarsson-Östling et al. (2017).

• The estimated emissions for buildings in each scenario should be 100 kgCO2e/person.year.

[4] Available at https://ars.els-cdn.com/content/image/1-s2.0-S0016328717301210-mmc1.docx

In essence, parameters are adjusted to reach the quota in four different ways, illustrating how the climate target could be reached in each scenario. These four sets of parameters are then used as a basis for discussing key strategies and issues to address so that buildings develop in a way that is compatible with ambitious climate change targets.

3.2 Survey and interview of municipalities within the Toolbox program

3.2.1 The “Toolbox for market implementation of LCA in building construction” research program

The Toolbox research program[5] aims at promoting LCA-based decision support in procurement for construction projects. The Toolbox program builds on recent estimations showing that the climate change impact of construction materials and processes for some newly-built apartment buildings could be about as large as the impact of operational energy use over 50 years of operation (Larsson, Erlandsson, Malmqvist, & Kellner, 2017; Liljenström et al., 2015). It is therefore highly relevant to use LCA-based tools to choose design solutions, materials and processes with low environmental impacts. The Toolbox program has a clear focus on decision support for practitioners, with the goal of leading to a broader adoption of life cycle perspective by construction sector practitioners and by municipalities, both in their planning role and in municipal procurement.

3.2.2 Overview of the survey and interview study

The study carried out within the Toolbox program addressed the second research question in this thesis. It focused specifically on the target audience of municipal practitioners, including both planners and developers for municipal construction projects. The aim was to investigate the current practices of municipalities with regard to environmental requirements for new construction projects, and identify the main barriers to the use of such requirements.

A distinction was defined between requirements set as public authorities (i.e. requirements that the municipality would set during planning, applying to all developers building in an area)

[5] https://www.e2b2.se/forskningsprojekt-i-e2b2/material/verktygslaada-foer-livscykelanalys-i-byggandet/

and as developers (i.e. in municipal procurement and the construction of public buildings such as schools). Another distinction concerned the type of requirement set. Prescriptive requirements necessitate newly-constructed buildings to have certain technical properties (e.g. have a timber frame). Information requirements necessitate the provision of data (e.g. a bill of resources). Performance requirements necessitate buildings to reach a certain level of performance defined by a given indicator (e.g. climate change impact calculated with LCA procedures).

The study investigated the most common practices among Swedish municipalities using a survey and semi-structured interviews, and identified the main barriers to a broader use of environmental performance requirements among municipal practitioners. Particular focus was on LCA-based requirements to promote construction with low climate change impact. Results of the survey and interview study were published in Paper 2, including a suggested strategy to overcome the identified barriers.

My work consisted of developing and carrying out the survey, exploiting the survey results, and designing the interview template. I did not carry out the interviews myself. They were carried out by Mattias Larsson and Josefin Florell. However, Mattias Larsson passed away during the project and Josefin Florell was not involved in writing the article. I therefore worked on exploiting the interview results based on transcripts.

3.2.3 Online survey

The first step in this study was to survey municipalities about their current practices related to limiting climate change impact from construction materials. The first purpose of this survey was to get a quantitative picture of the current situation, e.g. concerning municipal practitioners' knowledge with the issue, the types of measures currently implemented and the willingness of municipalities to work further with the issue. The second purpose of the survey was more exploratory: it allowed identifying issues of interest that could be explored further during the interviews, as well as respondents with insightful answers that could be contacted for interviews.

Guidelines from Sue & Ritter (2012) were considered in the design of the survey. The survey started with questions about the existence of a policy document dealing specifically with environmental issues from construction, and about the respondent's level of knowledge on this issue. It continued with a question about the policy instruments used by the municipality to promote construction materials with low climate change impact, as well as the measures that have been tried in the past, or that the municipality might try in the future. The final question specified the type of criteria used by the municipality (prescriptive, information or performance criteria). The survey was sent out to all Energy & climate advisors in Swedish municipalities, since each municipality is required to employ one such advisor. Energy & climate advisors were not necessarily the most suitable employees to answer the survey as they do not work directly with policymaking; they were therefore asked to forward the survey to a colleague if they could not answer it themselves. Results were analyzed after two reminders were sent out.

The results were analyzed to determine whether the answers given are sensitive to the size of the municipality (in terms of population). Municipalities were sorted into 3 categories (Large, Medium, Small) corresponding to the top, middle and bottom population tertile of the set of all Swedish municipalities, respectively. The Kruskal-Wallis statistical test was used to determine whether values in one category were significantly different from values in another category (Kruskal & Wallis, 1952). When the Kruskal-Wallis test was positive, the Dunn test was used to determine more in detail where the difference lies (Dunn, 1964). This allowed highlighting what aspects of the municipalities' work with environmental requirements in construction correlate with the municipality's size.

3.2.4 Semi-structured interviews

Semi-structured interviews were carried out to find out more about the respondents' experience with and opinion about environmental performance requirements in construction, in particular requirements based on a life cycle approach. Respondents that gave insightful answers to the survey or with whom the researchers were already in contact were interviewed in priority. 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 interviews were recorded, transcribed, and quotes were classified into themes reflecting the main points of interest for the study (Miles & Huberman, 1994; Vaismoradi, Turunen, & Bondas, 2013). The themes included for instance the overall strategy of the municipality, available resources, internal skills, collaboration between stakeholders, previous experiences, future prospects, perception of their role and of the role of national authorities, etc.

When carrying out a semi-structured interview focusing on the interviewee's opinion and perception of their "life world", the interviewer should usually adopt a reflexive approach. This entails a careful and in-depth examination of the results and the researcher's own approach, considering different ways of understanding the interview in its social context (Alvesson, 2003). However, the point of this specific interview study was to gather descriptions from key municipal practitioners and information about their work and experience with environmental requirements. Therefore, the interviewee's "life world" was less in focus and reflexivity mattered less than making sure key practitioners are interviewed. Since I did not carry out the interviews myself, having a more in-depth reflexive approach would have been difficult. Still, I analyzed the interview transcripts and reflected upon the validity of interview findings, notably in terms of the interviewees' political agenda and possible desire to appear environmentally conscious or give a positive image of their municipality.

The practices of two of the interviewed municipalities, Stockholm and Växjö, were studied more in-depth based on both interview results and online documentation. These two municipalities were chosen because of their extensive work respectively with requirements on environmental performance of buildings and on the use of a specific construction material (timber). Since they are large municipalities who have invested time and resources into testing and developing these requirements, they can be considered critical cases: if implementation barriers remain even for these municipalities, it is likely that similar barriers would arise in municipalities with less resources and less dedicated policies. On the other hand, if they managed to overcome such barriers, the cases can be used to suggest potential success factors for the implementation of environmental performance requirements. Although these learnings would be very dependent on the context of each municipality, context-specific knowledge is important to develop expertise about a subject (Flyvbjerg, 2006).

A weakness in the selection of interviewees, admittedly, was that small municipalities were not represented and only one medium municipality was represented. Their perspective might therefore not be adequately investigated. However, smaller municipalities often did not work with environmental requirements in construction according to the survey results.

4 Results

This section presents the main results from the research work. It is organized to address each research question in turn.

4.1 Key aspects of a building sector compatible with climate change mitigation

This first research question was addressed in Paper 1. Key aspects of buildings were quantified for each of the four backcasting scenarios of the Beyond GDP Growth project previously described in Gunnarsson-Östling et al. (2017), in line with the target of decreasing GHG emissions from Swedish consumption by 92% by 2050. Four sets of parameters were developed for the spreadsheet model, corresponding to four different ways for buildings to reach the emission quota of 100 kgCO2e/person.year, one for each scenario. These four sets of parameters were then used as a basis for discussing key strategies and issues to address for buildings to develop in a way that is compatible with an ambitious climate target. Analysis of the model results provided insights into key issues related to the climate change impact of buildings, which served as a basis for discussion.

4.1.1 Future energy supply

The first key issue is decarbonating the energy mix. It is a necessary precondition for target fulfillment in any scenario, even though energy use per m2 was significantly reduced in every scenario. This entails phasing out all fossil fuel-based electricity and heat production, as well as reducing the amount of non-biogenic waste incinerated. In the Beyond GDP Growth scenarios, this was mostly achieved through a high proportion of hydropower and biofuels in the electricity mix. However, transitioning to a fully renewable energy mix could give rise to issues of cumulative embodied emissions for the construction of renewable power plants (especially for photovoltaics), and issues relating to the exploitation of forests in order to produce biofuels.

The results suggest that cumulative embodied emissions, while not a daunting issue, are significant. Cumulative emissions from investments in new power plants, especially solar power plants, outweigh cumulative embodied emissions from building construction prior to 2050. Moreover, the timing of emissions matters and cumulative radiative forcing at a given future date is higher if emissions happen earlier (Brandão et al., 2013; Cherubini, Guest, & Strømman, 2012). This suggests that cumulative embodied emissions before 2050 should be given attention, and that simply fulfilling an emission quota in 2050 is insufficient.

Additionally, the amount of biomass needed for energy supply in each scenario was estimated. It appears that demand would not overshoot the carrying capacity of Swedish forests. Although the share of biomass in the energy mix is high in all scenarios, the total demand of bioenergy would be lower than today due to energy efficiency measures. Bioenergy use might therefore not be an issue, assuming a significant reduction in energy demand. However, issues such as the exploitation of forests for the pulp and paper industry and the need to leave forests unexploited to preserve biodiversity have not been considered. Helin, Sokka, Soimakallio, Pingoud, & Pajula (2013) found that the exploitation of forests might present higher environmental drawbacks than what is usually assumed for timber and biofuels, when considering long-term dynamics of carbon storage in soil and trees rather than a product perspective.

GHG emissions in the spreadsheet model are not very sensitive to operational energy use, because emissions per kWh are very low. This makes measures such as extensive renovation for energy efficiency ineffective to reduce GHG emission in 2050, because these measures increase emissions from construction materials while not significantly decreasing emissions from operational energy. However, it should be kept in mind that the baseline level of energy efficiency in every scenario is still significantly better than today. More energy use means a higher sensitivity of GHG emissions to the energy supply, a lower resilience, higher cumulative embodied emissions and a higher exploitation of forests for bioenergy. This suggest that reducing energy use is important in itself. There might therefore be tradeoffs and conflicts between environmental aspects. Renovation is a measure that reduces energy use in 2050, and therefore might reduce the demand for biomass in the future, but it could also increase cumulative embodied GHG emissions before 2050.

4.1.2 Emissions from construction and renovation

The second key issue is the rising importance of emissions from construction and renovation as the energy supply becomes less carbon-intensive. GHG emissions from operational energy use have often been cited as the main contributor to the climate change impact of buildings (Adalberth, Almgren, & Petersen, 2001; Sharma, Saxena, Sethi, Shree, & Varun, 2011), but recent developments show the increasing importance of the impact of construction (Anand & Amor, 2017; Birgisdottir et al., 2017; Ibn-Mohammed et al., 2013; Larsson et al., 2017; Liljenström et al., 2015). The present results also point to a rising importance of emissions from construction and renovation in relation to operational emissions. When the energy mix becomes less carbon intensive, the impact of the operational phase directly decreases, and the relative importance of the construction phase increases. Furthermore, for the same total amount of GHG emissions, cumulative radiative forcing at a given date is higher if these emissions happen in the construction phase rather than in the operational phase, because GHG are released earlier. Therefore, it is important to reduce emissions from construction in addition to emissions from operational energy use.

Reducing GHG emissions from construction materials can entail e.g. using concrete formulations with furnace slag or fly ash to reduce clinker content, reusing construction materials after deconstruction, increasing the use of less carbon-intensive materials such as timber in building frames and straw bale for insulation. Innovative solutions including e.g. 3D-printing techniques could also reduce the impact of construction (Rahimi, Arhami, & Khoshnevis, 2009). Initiatives such as the recent competition from the Swedish EPA to design a bridge over the Öresund strait with net zero GHG emissions are launched to experiment with new designs and materials (Swedish Environmental Protection Agency, 2018). Carbon capture and storage (CCS) is also being developed within the cement industry, but this technology was not discussed in the Beyond GDP Growth program (Koring et al., 2013). Another strategy to decrease the overall environmental impact of construction is to avoid new construction as much as possible, by retrofitting existing buildings, promoting flexible and adaptable design and optimizing the use of standing buildings.

4.1.3 Optimized use of space

In all scenarios, floor area per person needs to significantly decrease in both homes and workplaces. Optimized use of space has a considerable impact on GHG emissions from buildings, because they decrease the needs for heating, lighting, and new construction. Larger floor areas, on the contrary, make GHG emissions very sensitive to assumptions about the carbon intensity of the energy supply, because they increase operational energy use (although both small areas and clean energy supply are needed to reach the target). Reductions in floor area per user can be achieved if:

• more people live in apartments rather than houses

• facilities are shared between many users

• buildings are used throughout the day with little idle time

• space is highly optimized and dwellings retain an acceptable level of comfort in a much smaller space.

Reducing floor area is the only measure mentioned in article 1 that reduces GHG emissions in 2050, operational energy use and cumulative embodied emissions altogether, without requiring a tradeoff between these three aspects. However, it is also a measure that is difficult to implement to a large extent. The assumed reductions in floor areas in article 1 were considerable in some scenarios, which inevitably entails lifestyle changes. In other words, it appears necessary to plan to live in smaller spaces with shared areas.

4.1.4 Summary of findings

In short, GHG emissions in 2050 in all the scenarios seemed to be particularly sensitive to three factors, which much therefore be addressed in climate change mitigation strategies for buildings. First, the energy supply of buildings needs to rely on low-carbon sources. Second, construction should be avoided when possible or performed with low-climate change impact materials. Third, building design and lifestyles need to evolve so that space is used much more efficiently. Meeting the emission target therefore requires a combination of strategies. Energy supply issues often attract much attention from stakeholders and policymakers. Cleaner construction materials are not as popular an issue, but there are initiatives within the construction industry to develop low carbon products and optimize material use. On the other hand, avoiding construction and using space more efficiently aren't issues that attract much attention from policymakers or the construction industry.

This modelling exercise therefore allowed to shift the focus of the debate. It pointed out relevant issues that are underrepresented, and raised the question of possible conflicts between targets such as reducing GHG emissions, preserving forests and lowering energy use. It clearly suggested that incremental efficiency improvements in terms of energy supply and demand are insufficient; much more ambitious changes in lifestyles and urban planning seem to be required. It should however also be kept in mind that other common measures such as energy efficiency improvements in buildings also played an important role in all scenarios. Although GHG emissions in 2050 were not sensitive to further improvements in energy efficiency beyond baseline scenario assumptions, all scenarios assumed a higher energy efficiency level than today, and energy efficiency also played an important role in limiting resource use and increasing resilience.

4.2 Barriers to municipal requirements promoting construction with low climate change impact

This second research question was addressed in Paper 2. The main strengths and barriers that municipalities perceive in their work with environmental requirements in construction were identified, and a strategy to overcome these barriers was suggested. Particular focus was on performance requirements based on LCA tools and methods.

A survey of Swedish municipalities revealed significant differences in the number of measures municipalities implement to promote construction with low climate change impact, depending on the municipality's size. Municipalities worked most often with procurement, dialogue with stakeholders, and the provision of guidance and tools. In most cases where municipalities set environmental requirements in construction, they prescribed the use of specific designs and materials. On the other hand, measures related to the municipality's role as an authority and to the use of environmental performance requirements were very rare. The interviews revealed several barriers to the use of LCA-based environmental performance requirements, which can be summarized into the following categories.

4.2.1 Barriers related to skill and data

The interviews showed that LCA-related methodological skills are lacking among municipalities. The largest municipalities reported internal knowledge of LCA within their organization, but even then it varied widely between project leaders and the municipalities relied on hiring external consultants. Besides, lacking data and standards also appeared as clear barriers to LCA-based environmental performance requirements. Material inventory data is often unavailable or of poor quality, leading to unreliable results. Assessments can be performed based on different methodological choices and assumptions, which hinders comparability.

These barriers are similar to barriers to the use of LCA in the construction sector that were identified ten years ago in Stockholm (Brick, 2008). Some solutions suggested to address these issues included pilot projects to encourage material producers to publish better data and build experience, requiring data to be provided according to specific guidelines, and fostering cooperation, dialogue and the sharing of information between stakeholders. Raising in-house awareness and skill levels is often mentioned as a key measure also within the field of green procurement (Testa, Annunziata, Iraldo, & Frey, 2016; Testa, Iraldo, Frey, & Daddi, 2012; Walker, Di Sisto, & McBain, 2008).

4.2.2 Barriers related to time and resources

In relation to the previous aspect, addressing data and knowledge gaps is time-consuming and costly. Standardized procedures need to be established, staff needs to be trained, assessments need to be performed for a range of construction materials, etc. A respondent from a smaller municipality clearly expressed that they don't have the resources required to build up knowledge. The largest municipalities do have ongoing knowledge-building processes; their respondents saw themselves as having a role as forerunners in sustainability issues and they believed that their size gives them the means to really influence the practices of construction companies and smaller municipalities. Costs are of course also a key issue for developers and constructors: there is a perceived risk that setting environmental requirements would increase construction costs, limiting buy-in from stakeholders. Cost issues are commonly mentioned as one of the main barriers to sustainability oriented measures in organizations, limiting for instance the establishment of energy and climate strategy in municipalities (Wretling et al., 2018) and the uptake of green procurement in the private sector (Appolloni et al., 2014).

4.2.3 Barriers related to governance and the law

Beside concrete questions related to the availability of data, skills, time and resources, the action of municipalities can be limited by inadequate guidance at the national level and by the legal context surrounding their action. Some municipalities consider that environmental performance requirements are too complex to be handled at their level: they argue that guidance and standardization should happen at the national level. Besides, it is sometimes unclear whether municipalities are legally allowed to set such requirements, and they therefore fear legal prosecution.

Municipalities can freely set requirements when acting as a land and property owner and in their own procurement practices, as long as they respect rules pertaining to free competition. When developing plans, land allocation and exploitation agreements, setting any requirement that hinders free competition or overwrites requirements in the Building Code or the Planning and Building Act is illegal. The municipality is also expected to follow the Building Code by the letter when issuing building permits.

However, interpretations of the Planning and Building Act differ regarding whether these restrictions also apply when establishing detailed development plans. Additionally, it is sometimes unclear whether setting requirements on aspects that aren't already regulated in national codes would be legal. For instance, it could be argued that setting a GHG emission quota for construction materials in land allocation agreements is legal since this aspect is not otherwise regulated by the law. It could also be argued that such a requirement adds a higher ambition level than the building code and is therefore illegal.

Once again, similar issues are mentioned in other studies.

Wretling et al. (2018) mention that an unfavorable legal context limits the development of municipal climate strategies. Walker et al. (2008) showed that compliance with regulations can be perceived as a threat to green procurement. Faith-Ell, Balfors, & Folkeson (2006) showed that environmental requirements in road maintenance are hampered by poor communication between national and local authorities.

4.2.4 Summary of findings

The main barriers that municipal practitioners face when working with environmental requirements in construction relate to skill, data, resources and guidance. There seems to be a need for inventory data for LCA that is transparent, easily accessible and of higher quality, as well as standardized methods and procedures adapted to the practitioners' needs and skill level. When these are lacking, assessments are difficult to carry out, difficult to compare and sometimes highly uncertain.

Although municipalities are relevant actors to deal with sustainability issues, their lack of resources can seriously hamper their work, unless they are particularly large. It should also be kept in mind that setting environmental requirements can create conflict with developers and constructors if dialogue and cooperation processes are not established. It could also increase construction costs, which is an undesirable outcome in a context of urbanization and housing crisis in large cities: the decision to set environmental requirements should therefore be carefully considered and be progressively implemented in collaboration with construction sector stakeholders. Finally, a lack of guidance at the national level and an ambiguous legal context seem to lead some municipalities to err on the side of caution and avoid setting requirements altogether.

5 Discussion

5.1 Strategic decision support

The overarching aim of the thesis has been to support strategic decisions to reach climate change mitigation targets in the building sector. Overall, my reasoning is based on considering various strategic issues to be dealt with in order to reach environmental targets, as illustrated in Figure 1. The present thesis addressed two of these issues: establishing suitable strategies and solving practical issues to implement these strategies (in particular at the municipal level).

Both papers presented have implications for policymakers and practitioners. The modeling of backcasting scenarios in Paper 1 highlights issues that should be in focus when establishing sustainability strategies for buildings. It reinforces arguments about the importance of decarbonating the energy mix, and adds to a body of recent studies indicating the rising importance of reducing climate change impact from construction materials (Anand & Amor, 2017; Birgisdottir et al., 2017; Ibn-Mohammed et al., 2013; Larsson et al., 2017; Liljenström et al., 2015). Moreover, it directs the attention of policymakers and

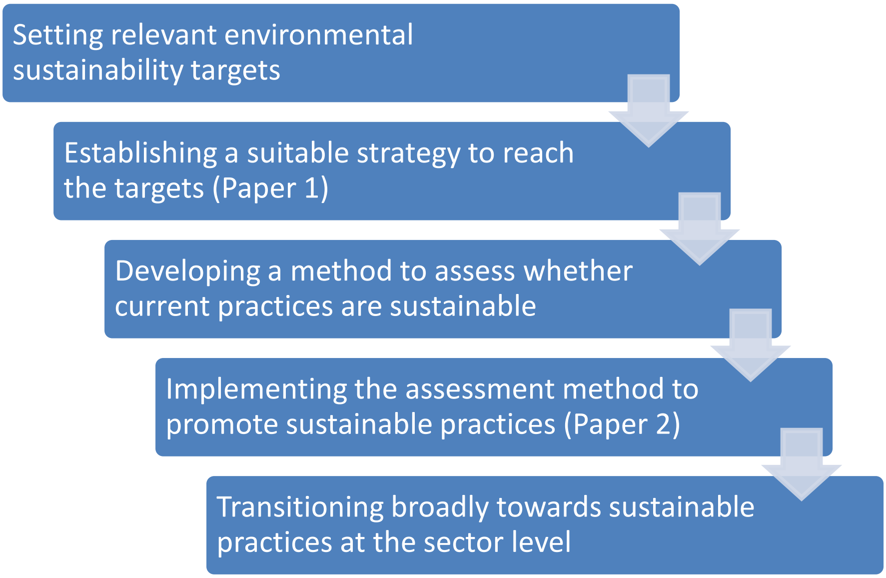

Figure 1 - Strategic issues related to environmental sustainability considered in this thesis

practitioners towards important issues that might otherwise be neglected in debates about sustainable buildings, such as avoiding new construction and optimizing the use of space.

A combination of strategies is necessary to reach an ambitious climate target: technological improvements for energy supply, materials and insulation will have to be complemented with significant changes in lifestyles and building design, including living in smaller spaces, sharing space or using flexible offices. Energy efficiency measures that are a key part of current sustainability strategies provide less climate benefits once a certain level of efficiency and decarbonation of the energy supply has been reached.

A critical examination of this result highlights another aspect that receives little attention in current debates. GHG emissions are the focus of many sustainability strategies, but climate change is not the only pressing planetary boundary (Steffen et al., 2015). The study points out possible conflicts between reduction of GHG emissions and sustainable land use (due to the exploitation of forests for bioenergy and timber construction). The relevance of energy efficiency beyond reducing GHG emissions is also considered: with a very low-carbon energy mix, energy efficiency should be considered from other angles, such as preserving natural resources, reducing costs and improving the resilience of the energy system.

By highlighting these ideas in the current discourse on what makes a building sustainable, the modeling study and the Beyond GDP Growth project allow changing perspectives and questioning what issues are on the agenda. The backcasting scenarios are therefore a tool to help discussions about sustainability strategies. Different scenarios could have been developed and could have brought a different input to the discussion. The very process of developing scenarios can therefore impact strategic choices.

The survey and interview study in Paper 2 highlights very concrete logistical and legal issues that can hinder the implementation of sustainable practices. Developing sustainability strategies isn’t enough: there is also a need to create the conditions of their implementation. The study led to recommendations to facilitate the implementation of LCA-based environmental requirements in municipalities, as illustrated in Figure 2.

These recommendations focused on overcoming three types of barriers, related to resources, conflicts and knowledge respectively. In order to ensure that the municipality has enough time and budget to carry out the implementation process, the first step should entail securing resources and external help and setting appropriate targets. The municipality could receive guidance from national authorities or start a joint initiative with neighboring municipalities. If resources are scarce, it can be appropriate to limit ambitions and set prescriptive requirements in procurement, which are easier to manage.

The municipality should then establish a dialogue with developers and constructors. This ensures that all actors are in agreement about why requirements are set, what the objectives and the municipality's strategy are and what assessment methods shall be used. Collaboration with both private sector practitioners and national authorities also limits the risk of legal issues.

In order to bridge knowledge and data gaps, the municipality can then require developers and constructors to provide inventory data for new construction projects. The municipality should make sure that appropriate guidance and standardized methods are easily available. Information requirements can be strengthened over time, as practitioners become progressively more familiar with data collection and LCA methods. Whenever requirements are strengthened, it is important to ensure continued dialogue and collaboration with stakeholders.

When data and knowledge gaps are filled and the environmental performance of buildings can be routinely assessed and compared, the municipality can set environmental performance requirements for new buildings. When setting requirements, the municipality should be careful about the legal context. For procurement and municipal construction projects, the municipality must ensure fair competition when selecting tenders. Integrating information and performance requirements into e.g. detailed development plans or land allocation agreements can reach a broader audience and have a larger impact, but legal issues can arise depending on the formulation of the requirement.

These results are not only relevant for municipal practitioners. They should also be taken as an indication for national actors that guidance and an appropriate regulatory context are required for local actors to work with sustainability issues. Similarly, private sector practitioners should be encouraged to collaborate with public authorities to progressively increase sustainability requirements in construction while making sure they are provided with appropriate assessment tools.

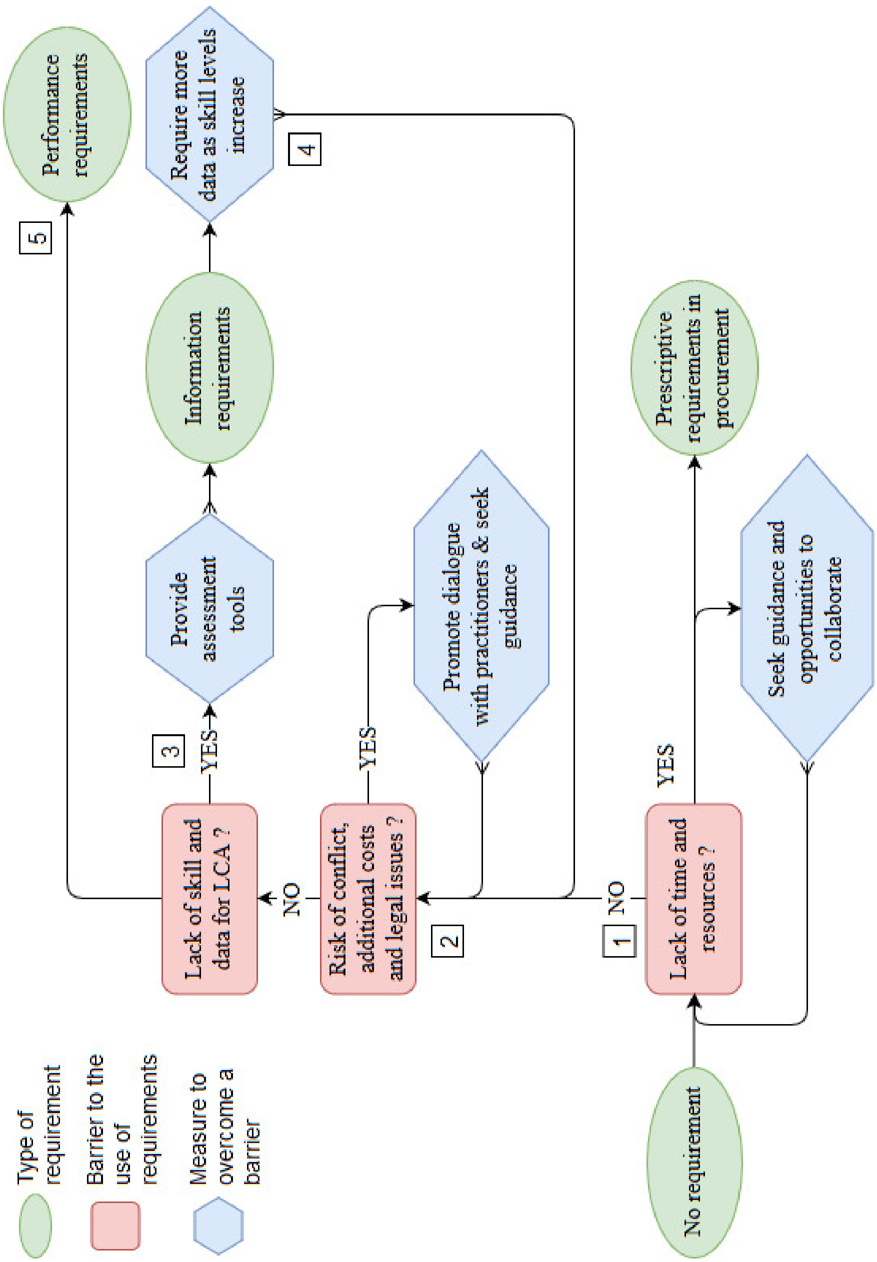

Figure 2 - Simplified flowchart representation of a stepwise strategy to implement environmental performance requirements in municipalities (a more complete picture is included in Paper 2)

5.2 Remaining gaps

This thesis addressed two specific strategic issues related to environmental sustainability, as represented in Figure 1. This section discusses some strategic issues that still need to be addressed in the light of this thesis. It considers remaining gaps and potential needs for future research related to setting sustainability targets, assessing the environmental performance of current choices, and initiating broad sector-wide changes in practices.

In this licentiate thesis, climate change mitigation targets at the global, national and municipal level were taken for granted. However, setting an appropriate target is in itself a key task. The first question to consider is choosing what issue to assess. Steffen et al. (2015), describing the Planetary Boundaries framework, consider climate as a core environmental aspect because its state impacts and is impacted by many other environmental aspects. However, biosphere integrity is also one such core aspect. Setting a target for e.g. biosphere preservation instead of climate change mitigation would likely lead to different recommendations, especially considering that bioenergy and timber construction might benefit the climate but damage the biosphere. The task becomes even more complex when considering social issues. The Doughnut framework thus highlights possible tradeoffs between environmental and social issues (Raworth, 2012). For instance, closing a highly-emitting factory to mitigate climate change could lead to unemployment and an increase in poverty. Although the focus of this thesis has been climate change impact, it can provide insights for other sustainability issues as well. In particular, LCA-based criteria in procurement, certification and environmental requirements could cover other impact categories besides climate change impact. The practical barriers to the implementation of LCA-based environmental performance requirements are therefore likely to be relevant for other sustainability issues as well.

Another question to consider is how to formulate and quantify the target. This issue arises in particular when narrowing down a global target into a specific sector or geographic area. The results of Paper 1 are based on the assumption that per capita GHG emissions in Sweden in 2050 would be equal to the world average used in a climate mitigation scenario, and that the share of buildings in these emissions would be the same in all scenarios. The key building aspects highlighted as a result could be different if one argues e.g. that one scenario should include lower GHG emissions for buildings but higher emissions for transports. Paper 2 also indicates that the global climate target is reflected in many different ways in municipal targets. Some municipalities set targets to phase out fossil fuels, others to promote timber construction, others to limit GHG emissions in a production and/or consumption perspective, etc. These different targets in turn lead to different strategies. For instance targets that relate directly to GHG emissions give a better idea of the actual climate impact but tend to be more difficult to follow up than targets based on concrete measures like phasing out fossil fuels.

Assuming a GHG emission target has been set, the question remains of assessing whether a decision taken today by a practitioner will help fulfilling the target. This step bridges the broad strategic point of view of Paper 1 and the concrete focus on current practices in Paper 2. A valid and easily usable method must be available to assess the impact of buildings. LCA could be used for decision support. This requires appropriate data to be easily available, valid and transparent, and LCA tools to be standardized and easily usable by practitioners. Improvements have been achieved in that sense in recent years. The Swedish Transport Administration requires an LCA to be carried out for infrastructure projects costing more than €5 million, and provides a calculation tool with data and templates (Swedish Transport Administration, 2016). Regarding buildings, the BM tool has been developed in Sweden to estimate GHG emissions from construction materials and processes, with a focus on simplicity, ease of use, free access and a built-in database (IVL Swedish Environmental Institute, 2018). Issues remain in LCA regarding the validity of data (e.g. using specific data for products instead of broad generic data), its transparency, its ease of access (e.g. being able to easily and freely download data for spreadsheet calculations) and the standardization of assessments.

LCA from various sources are only useful insofar as they are comparable: assessment methods must therefore be standardized to make sure all practitioners are on the same page. Norms such as EN15804 and EN15978 regulate environmental product declarations (EPDs) for construction materials and calculation methods for building LCA respectively. Still, a number of methodological aspects are not yet standardized internationally. The Annex 72 task in the International Energy Agency's Energy in Buildings and Communities program aims at establishing common methodological guidelines for building LCA and methods for the development of national benchmarks and databases (International Energy Agency, 2018). Issues include how the impact of recycled material is considered, how to set the expected lifespan of the building and the frequency of refurbishment, whether to weight differently emissions happening at different points in time, or what assumptions should be made regarding the future energy supply of the building. For each of these aspects, choosing a method over another can significantly impact the results and recommendations made. The influence of various methodological choices on what building practices are considered sustainable deserves closer scrutiny.

Last but not least, practices have to be broadly adopted by practitioners to be impactful. This means that standardized assessment tools also need to take into account complexity, user-friendliness and the specific needs of practitioners. In order to promote learning and competence building, the Swedish National Board of Housing, Building and Planning has recently proposed to implement a standardized climate declaration for all new construction projects (Swedish National Board of Housing Building and Planning, 2018).

This issue also calls for an analysis of how to initiate a large scale transition to change practices within the building sector. I have contributed to this by identifying barriers to LCA-based environmental performance requirements in Paper 2, and suggested solutions to overcome them. However, future research could investigate the adoption of sustainable building practices from other theoretical points of view. Insight could for instance be gained from adopting a multi-level perspective (MLP), which considers transitions through the lens of interactions between processes at the niche level (local radical innovations), the regime level (established practices) and the landscape level (exogenous conditions) (Geels, 2011). There has been much research concerning transitions brought about by nurturing niche innovations, although the importance of processes at the regime and landscape levels has been recognized (Boyer, 2015; Geels & Schot, 2007).

Another useful approach could be institutional theory, which describes how organizational practices are influenced by institutions inside and outside of the organization, including regulations, shared expectations and routinized behavior (Berthod, 2016). Recent research has investigated institutional change in particular, including how and why institutions change and what role is played by organizations and individual actors in these processes of change (Berthod, 2016; Dacin, Goodstein, & Scott, 2002). These are only two among many possible ways of analyzing the issue of changing practices within the building sector.

6 Conclusion and key takeaways

This licentiate thesis investigated how policymakers and municipal officials could influence the construction and operation of buildings to reach ambitious climate change mitigation targets. A first contribution in that regard has been highlighting a list of aspects of particular importance for the built environment to develop in an environmentally sustainable manner, and discussing how these aspects could be addressed in various future scenarios. The key results were as follows:

• Having a very low-carbon energy supply is necessary, but not sufficient, to reduce GHG emissions in accordance with the 1.5°C target. Using bioenergy demands careful consideration to make sure the climate target does not conflict with targets in terms of e.g. biodiversity and land use.

• Reducing GHG emissions from construction materials becomes a key issue. GHG emissions from operational energy use become less prominent due to a low-carbon energy supply and efficiency measures and are sometimes outweighed by emissions from construction. These must be reduced by using less carbon-intensive materials and optimizing construction processes.

• Space efficiency appears to be important for target fulfillment in all scenarios. This implies an increase in density and frequency of use of space, i.e. a decrease in floor area per user and idle time. Space sharing and optimization of building use could be important components of a sustainability strategy for buildings, even though they are not spoken much of today.

• Energy efficiency improvements in renovation and new construction are necessary in all scenarios. Once a low-carbon energy supply is in place, carrying out very extensive energy renovation can become ineffective to reduce GHG emissions. However, it can still lead to reduced resource use (e.g. of biomass) and improved resilience.

A second contribution has been to investigate barriers to environmental requirements in municipalities and propose an implementation strategy for LCA-based environmental performance requirements. The key results were as follows:

- Some municipalities work actively with promoting construction with low climate change impact. Large municipalities implement more measures than small ones. Municipalities usually act in their own procurement, not as public authorities.

- All municipalities face barriers related to a lack of in-house skills, access to data, limited resources, ambiguities regarding the law and a lack of guidance from national authorities. The largest municipalities can have a role as forerunners and initiate projects to bridge skill and data gaps and influence constructors, but even they experience these barriers to some extent.

- A strategy was suggested to overcome these barriers. First, the lack of resources should be addressed by setting appropriate ambition levels, seeking support from national authorities and collaborating with other municipalities. Second, conflicts and legal uncertainties should be prevented by promoting collaboration with private sector stakeholders and by seeking legal clarifications from national authorities. Third, the lack of skill and data should be addressed by setting information requirements and progressively require constructors to provide LCA data until environmental performance can routinely be assessed.

Although there are other issues related to sustainability strategies, I have therefore contributed to addressing two issues: ensuring strategic decisions for sustainability in the building sector consider all important aspects, and implementing assessments of environmental performance of buildings in practice.

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