Towards Low-Carbon Design in the Building Sector

Investigating method and benchmark for life cycle greenhouse gas emissions from renovation and the integration of digital tools in the design process

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BY
REGITZE KJÆR ZIMMERMANN

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
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ENGLISH SUMMARY

Climate change is becoming increasingly more visible around us, with record-setting phenomena such as high temperatures causing heatwaves and wildfires across the world. The human-caused climate change negatively affects the planet with serious consequences, often affecting socially and economically marginalized residents. With the Paris Agreement, nations will pursue efforts to limit the global average temperature to 1.5˚C above preindustrial levels and well below 2˚C. To accomplish this requires immediate cuts in emissions across all sectors. Buildings and construction are responsible for almost 40% of energy-related CO_2 emissions, thus offering a significant mitigation potential by decarbonizing material production and operational energy while also improving the design of new and existing buildings.

To effectively improve the design of new and existing buildings in the building sector, we need accurate and fair methods for assessing life cycle based greenhouse gas emissions (GHGe), especially for renovation projects where method development lags behind. Further, we need effective ways to integrate the assessment into the design process. In this dissertation, I have identified and evaluated significant methodological variations and challenges in relation to performing and benchmarking LCA of renovation and suggested how this can be implemented in practice to support future method development and policymaking. Furthermore, I have identified needs for future development of digital tools to integrate LCA in the design process and developed practical approaches.

To assess and show methodological challenges, 23 renovation cases are first assessed for their contribution to life cycle GHGe, considering the Danish context. The GHGe varied a lot between cases for both operational and embodied emissions due to the differences in renovation actions. The embodied emissions related to lowering the energy demand of the building is, on average, related to 46% of the embodied emissions. The remaining 54% of are related to other changes in the renovation projects, such as layout, indoor climate, and spatial changes. The results clearly indicate operational savings potential from renovation, which is supported by existing literature. The savings for these cases were between 20%-65%. However, it also shows the significance of embodied emissions in renovation, which are not related to energy reduction. While the political focus is on reducing energy demand, it is important that these potential impacts are considered in future renovation design and policy-making.

A typical renovation project was compared to demolition and new construction, using three different national approaches for assessing the GHGe of buildings. The results illustrated the significance of system boundaries in the assessment. Especially the inclusion of the operational energy use. The emissions from operational energy are significant to correctly assess the life cycle GHGe. However, due to their large impact

on the result, operational energy use can limit incentives to reduce upfront emissions. Reducing upfront emissions is important to limit temperature rise. Therefore, it is important to consider all modules from upfront emissions in climate declarations. Further, it should be considered to declare emissions separately for upfront and future emissions and improve modeling and uncertainty analysis for operational energy use.

For the consideration of benchmarks, the assessment of 23 real-life renovation cases showed that life cycle GHGe vary significantly for renovation projects, even though most of them are considered “major renovation”, according to the definition in the EPBD. The potential impacts from renovation projects relate to different added functions, making the renovation projects unique and varied. The differences in added functionality, along with the different conditions of the existing building, complicate the benchmarking of renovation projects on a building level. A more practical solution that can be implemented in the building sector is to consider benchmarks on a “smaller” level, such as the building elements and components.

For the practical integration in the design process, digital tools can be applied. The research showed that the inclusion of existing materials can add a significant workload to the performance of LCA on renovation projects. To ease the workload, a tool was created to automate the life cycle inventory of existing materials in buildings based on a generic library and a parametric geometry model. It helps automate the process of performing LCA for the early design stages and for projects where there is no detailed geometric model or BIM. It can also be used on a larger scale for building stock/material bank screenings.

Qualitative interviews were conducted with consultants in the Danish building industry for projects where geometric models or BIM exist. The interviews investigate current implementation strategies and challenges in BIM-LCA. Results showed that they mainly use a “quantity take-off” approach, which involves many manual processes. Further, they need to supplement the data from the models to improve accuracy and completeness. The manual processes are both time-consuming and cause human errors. Therefore, the industry needs a more automated integration process to avoid human errors but with transparency in order to easily find and fix errors from e.g., the model. The quick/automated process will be especially valuable in the early design stages.

The dissertation considers the temporal perspective and future uncertainties, which is of paramount importance for LCA on renovation projects. This is due to the nature of renovation projects, where especially energy renovations are a trade-off between upfront and future emissions. The dissertation also considers the current development of regulation, where EU initiatives such as the “renovation wave” and the changes in the energy performance of buildings directive (EBPD). With this current regulatory focus on increasing renovations, it is important to simultaneously reduce the embodied emissions from the materials used in the renovation. These legislative and global demands also put a large responsibility on digital tools that can address the demands which is currently ongoing in the industry.

The research presented in the dissertation shows methodological and practical challenges but also outlines possible directions to limit GHGe. In order to limit the rise in temperature, it is important that we reduce emissions quickly.

DANSK RESUME

Klimaforandringer bliver mere og mere synlige omkring os med rekordsættende fænomener som fx høje temperaturer, der forårsager hedebølger og naturbrande i mange dele af verden. De menneskeskabte klimaforandringer kan påvirke planeten negativt med alvorlige konsekvenser, der ofte påvirker socialt og økonomisk marginaliserede mennesker. Med Parisaftalen vil nationer bestræbe sig på at begrænse den globale gennemsnitstemperatur til 1,5˚C over præindustrielle niveauer og et godt stykke under 2˚C. Det vil kræve øjeblikkelige nedskæringer i emissioner på tværs af alle sektorer for at opnå dette. Byggeri er ansvarlig for næsten 40 % af den energirelaterede CO_2-udledning og tilbyder således et betydeligt reduktionspotentiale. Dels ved at dekarbonisere materialeproduktion og driftsenergi, og samtidig ved at ændre den måde vi renoverer og designer nye bygninger, så deres klimapåvirkning reduceres.

For at sikre, at vi reelt opnår en reduktion i klimapåvirkning ved nybyggeri og renovering af de eksisterende bygninger har vi brug for retvisende metoder til at vurdere livscyklusbaserede drivhusgasemissioner. Det gælder i særlig høj grad for renoveringsprojekter, hvor metodeudvikling mangler. Ydermere er der i byggeriet et stadigt stigende behov for effektive og tidsbesparende måder at integrere livscyklusvurderingen i designprocessen. I denne afhandling har jeg identificeret og evalueret væsentlige metodiske variationer og udfordringer i forhold til at udføre og benchmarke LCA af renovering, og hvordan dette kan håndteres i praksis i den videre udvikling. Derudover har jeg identificeret behov for fremtidig udvikling af digitale værktøjer til at integrere LCA i designprocessen, og udviklet praktiske tilgange.

For at undersøge og synliggøre de metodiske udfordringer ved renoveringsprojekter udføres der livscyklusvurdering af 23 renoveringsprojekter i en dansk kontekst til at vurdere deres klimapåvirkning. Klimapåvirkningen varierede meget mellem projekterne for både driftsenergi og indlejrede emissioner på grund af store forskelle i renoveringstiltag. De materialerelaterede klimapåvirkninger forårsaget af ønsket om at opnå en driftsenergireduktion bidrager i gennemsnit til 46% af de indlejrede emissioner. De resterende 54% af de indlejrede emissioner er relateret til andre renoveringsarbejder, såsom ændret indretning, forbedring af indeklimaet eller om- of tilbygninger. Resultaterne indikerer tydeligt at der er et driftsenergibesparelsespotentiale ved renovering, hvilket understøttes i eksisterende litteratur. For disse cases lå besparelsen på mellem 20-65%. Men det viser også at størstedelen af de indlejrede emissioner ved renovering, skyldes aktiviteter, som ikke har fokus på energireduktion. Så mens det politiske fokus er på at reducere energiforbrug, viser denne undersøgelse, at der også skal fokus på de samlede renoveringsaktiviteter for at undgå øget klimapåvirkning.

Et typisk renoveringsprojekt blev sammenlignet med en alternativ nedrivning og nybyggeri. Sammenligningen blev foretaget ved brug af tre forskellige nationale tilgange til at bestemme klimapåvirkning. Resultaterne illustrerede betydningen af systemgrænser, som varierede fra land til land. For eksempel viste resultaterne en følsomhed over for inddragelse af driftsenergiforbrug på grund af dets store indflydelse på resultatet. Emissionerne fra driftsenergi er afgørende for korrekt at vurdere de livscyklusbaserede drivhusgasser over hele bygningens levetid. Omvendt vil der ved en metode, som medtager driftsenergiforbruget være et begrænset incitamentet til at reducere de emissioner som sker her og nu den dag renoveringen påbegyndes. Og reduktion af emissioner, der sker her og nu, er meget vigtige for at holde os inden for planetens CO_2-budget. Derfor er det vigtigt at medtage alle emissioner, der sker her og nu, når bygningens klimapåvirkning skal bestemmes. Yderligere bør det overvejes at deklarere emissioner, der sker "i dag" separat, samt forbedre modellering og usikkerhedsanalyser, særligt for driftsenergiforbruget.

Livscyklusvurdering blev foretaget for 23 renoveringer fra virkeligheden i en dansk kontekst. Resultaterne viste, at klimapåvirkninger over renoveringernes livscyklus varierer betydeligt. Det på trods af, at de fleste af dem betragtes som "større renoveringer", ifølge definitionen i EPBD. De potentielle påvirkninger fra renoveringsprojekter relaterer sig til forskellige tilføjede funktioner i renoveringsprojekterne, hvilket gør de enkelte projekter unikke. Forskellene i tilføjet funktionalitet sammen med de forskellige udgangspunkter i forhold til den eksisterende bygnings standard og behov komplicerer udviklingen af reference- eller grænseværdier for klimapåvirkning af renoveringsprojekter på bygningsniveau. Derfor bør man overveje at implementere grænseværdier på et "lavere" niveau end bygningsniveau, fx for bygningsdele og komponenter. Dette vil også være lettere at implementere i praksis. Grænseværdier for bygningsdele kan laves med en "bottom-up" tilgang baseret på det eksisterende niveau, men kan evt. kombineres med en "top-down" tilgang baseret på det resterende CO_2-budget.

Digitale værktøjer kan anvendes til at opnå LCA-integration i designprocessen. Forskningen viste, at inddragelse af de eksisterende materialer kan tilføje en betydelig arbejdsbyrde til udførelsen af LCA på renoveringsprojekter. For at lette arbejdsbyrden for byggeriet blev der derfor skabt et værktøj til at automatisere livscyklusvurderingen af eksisterende materialer i bygningen baseret på et generisk bibliotek og en parametrisk geometrimodel. Værktøjet hjælper med at automatisere processen med at udføre LCA i de tidlige designstadier og kan bruges i projekter, hvor der ikke er nogen detaljeret geometrisk model eller BIM. Den kan også bruges i større skala til at lave fx materialebankanalyser.

Der er gennemført kvalitative interviews med rådgivere i den danske byggebranche. Her handlede det om generelle projekter, hvor der findes geometriske modeller eller BIM, herunder også nybyg. Interviewene undersøger aktuelle implementeringsstrategier og udfordringer i BIM-LCA. Undersøgelsen viste, at rådgiverne hovedsageligt anvendte en ”mængdeudtræk tilgang”, som involverer mange manuelle processer. Yderligere skal de supplere dataene fra modellerne for at forbedre nøjagtigheden og fuldstændigheden. De manuelle processer er både tidskrævende og resulterer i menneskelige fejl. Derfor har branchen brug for en mere automatiseret integrationsproces. Samtidig er der dog også behov for gennemsigtighed for nemt at finde og rette fejl som typisk findes i modellen. Den hurtige og automatiserede proces vil være særlig værdifuld i de tidlige designfaser, men også ved de mange og uundgåelige ændringer, som forekommer i projekterne.

I forhold til fremtidige klimakrav til renoveringsprojekter diskuterer afhandlingen også det tidsmæssige perspektiv og fremtidige usikkerheder med hensyn til driftsenergien, som er af afgørende betydning for LCA specielt på renoveringsprojekter. Det skyldes renoveringsprojekters karakter, hvor især energirenoveringer er en afvejning mellem emissioner i dag og fremtidige emissioner. Afhandlingen behandler også den aktuelle udvikling af regulering på klimaområdet, herunder bl.a. EU-initiativer såsom "renoveringsbølgen" og ændringerne i bygningsdirektivet. I den sammenhæng er det vigtigt samtidig at reducere de indlejrede emissioner i renoveringen. Disse lovgivningsmæssige og globale krav lægger også et stort ansvar på de digitale værktøjer, der skal imødekomme nuværende og kommende krav.

Forskningen præsenteret i afhandlingen viser metodiske og praktiske udfordringer, men skitserer også mulige retninger som kan følges for i praksis at begrænse bygningers klimapåvirkning. For at begrænse temperaturstigningen, er det vigtigt at vi reducerer emissioner hurtigt.

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PREFACE

This dissertation is the result of a project carried out at the Department of the Built Environment at Aalborg University from 2020 to 2023. The dissertation is based on a core collection of five publications that are presented in Chapter 1. The publications have a common focus on LCA of buildings in industry practice, within the topics of LCA methods and design process integration. The five core publications are complemented by a set of other publications that relate to these topics and were published during the PhD project. The complementary publications consist of the following publications:

Topic: Integration of LCA in the design process of buildings:

- “Learnings from Developing a Context-Specific LCA Tool for Buildings—The Case of LCAbyg 4”; Kanafani, Kai; Zimmermann, Regitze Kjær; Rasmussen, Freja Nygaard; Birgisdottir, Harpa; Published in Sustainability, 2021

Topic: Method and benchmark in LCA of buildings

- ”LCA-Framework to Evaluate Circular Economy Strategies in Existing Buildings”; Zimmermann, Regitze Kjær; Kanafani, Kai; Rasmussen, Freja Nygaard; Andersen, Camilla Marlene Ernst; Birgisdottir, Harpa; Published in IOP Conf. Series: Earth and Environmental Science, 2020
- “Whole Life Carbon Assessment of Renovation – Possibility of Specifying Benchmarks Values for LCA of Renovation work ” (Danish: ”Klimapåvirkning fra renovering: Muligheder for udformning af grænseværdier til LCA for renovering”); Lund, Alberte Mai; Zimmermann, Regitze Kjær; Kragh, Jesper; Rose, Jørgen; Aggerholm, Søren; Birgisdottir, Harpa; BUILD Report No. 33, 2022
- “The choice of reference study period in building LCA - Case-based analysis and arguments”; Rasmussen, Freja Nygaard; Zimmermann, Regitze Kjær; Kanafani, Kai; Andersen, Camilla Marlene Ernst; Birgisdottir, Harpa; Published in IOP Conf. Series: Earth and Environmental Science, 2020

Topic: Circular design strategies in LCA of buildings

- "Comparison of GHG emissions from circular and conventional building components"; Andersen, Camilla Marlene Ernst; Kanafani, Kai; Zimmermann, Regitze Kjær; Rasmussen, Freja Nygaard; Birgisdottir, Harpa; Published in Buildings and Cities; 2020

Acknowledgments

My PhD work started out during the global pandemic, in a summerhouse while taking online courses. I am now back at the office, writing this, and the time between has been both fun and challenging. I want to thank all the people who were there during this time. First to Harpa, who made it all possible, and who's infectious energy and commitment is an inspiration to work with. To Freja, for always stepping up to provide feedback and valuable guidance. To all my many great colleagues – previous and current - who's discussions, support, and collaboration I have enjoyed. And to friends and family for always being there for me.

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GLOSSARY

API	Application Programming Interface
BIM	Building Information Model
Copernicus	Copernicus Climate Change Service (the European Union's Earth Observation Programme)
CO_2-eq	CO_2-equivalents
DGNB	Building certification system (Deutsche Gesellschaft für Nachhaltiges Bauen)
EN 15978	European standard: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method
EN 15804	European standard: Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products
EoL	End-of-Life
EPBD	Energy Performance of Buildings Directive (European Union)
EPD	Environmental Product Declaration
GHGe	Greenhouse gas emissions
GWP	Global Warming Potential (environmental impact category measured in kg CO_2-eq.)
IFC	Industry Foundation Classes
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
RSP	Reference Study Period
UN	United Nations
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

CHAPTER 1. INTRODUCTION

1.1. THE CLIMATE CHALLENGE RELATED TO BUILDINGS

Climate change has become increasingly visible around us. As of writing this thesis in the summer of 2023, the current weather is described as "rather remarkable and unprecedented" by scientists from the European Commission's Copernicus Climate Change Service and the World Meteorological Organization due to its record-setting high temperatures in both air and sea (UN, 2023a). The surface air temperature for July is almost identical to estimates of 1.5˚C warming compared to preindustrial levels for July (Copernicus, 2023). This has caused heatwaves in Asia, Europe, and North America, causing wildfires and impacts on human health and the environment (WMO, 2023).

"All this is entirely consistent with predictions and repeated warnings. The only surprise is the speed of the change" - United Nations Secretary-General António Guterres on the record temperatures (WMO, 2023).

The atmospheric content of greenhouse gas emissions (GHGe) from human activities continues to rise, which is causing temperature rise on Earth. In 2019, there was an increase in global human-caused GHGe of 12% compared to 2010 and 54% compared to 1990 (IPCC, 2023). The global surface temperature is increasing faster than it has for at least 2000 years and is 1.09°C higher than pre-industrial levels for the period 2011-2020 (IPCC, 2023). Human-caused climate change can negatively impact water scarcity, food production, health, cities, and changes in ecosystems, including irreversible losses in ecosystems and loss of species (ibid). The impacts in urban areas are concentrated on socially and economically marginalized residents (ibid.). In 2015, the Paris Agreement was adopted by 196 Parties at the UN Climate Change Conference. The main goal is to keep "the increase in global average temperature to well below 2˚C above pre-industrial levels" and pursue "efforts to limit the temperature increase to 1.5˚C above pre-industrial levels" (UN, 2015). An increase of 2˚C is considered by scientists to have dangerous consequences for climate and the environment (European Parliament, 2023). Even crossing the 1.5˚C threshold can cause severe climate change impacts, which is why world leaders have recently emphasized the need to limit temperature rise to 1.5˚C (UN, 2023b). However, considering the current policies and laws for climate mitigation reported by nations, it is likely that 1.5˚C will be exceeded in the 21st century and make it difficult to stay below 2˚C (IPCC, 2023). Net zero emissions are required to limit human-caused global warming (ibid.). The cumulative carbon emissions until we reach net zero mainly determine whether we can stay below temperatures of 1.5˚C or 2˚C. An estimate of the remaining carbon budget in 2020 is 500 $GtCO_2$ for a 50% likelihood of remaining below 1.5˚C. If the CO_2-emissions of 2019 continue between 2020 and 2030, this budget will almost be exhausted (ibid).

There is hope to limit global warming if emissions are cut quickly. GHG emissions need to be cut by 43% in 2030 compared to 2019 emissions to stay below 1.5˚C (IPCC, 2023). To achieve this, action is required over numerous sectors. This includes the building sector, which is currently off target to achieve the Paris Agreement (UNEP, 2022). Globally, buildings and construction activities in 2021 are responsible for 37% of energy-related CO_2 emissions, where 9% represent material production for the construction and renovation of buildings (ibid.). The building and construction sector offer a significant global mitigation potential considered by the IPCC (IPCC, 2023). The mitigation is achieved by improving existing and new buildings and decarbonizing material production. Further, the operational emissions will need to drop by more than 95% (UNEP, 2022). In the EU, several legislations have been initiated to reduce the emissions from buildings and achieve the goal to have net zero emissions by 2050, which was stated in the European Green Deal (European Green Deal, 2019). The initiatives include an update of the Energy Performance of Buildings Directive (EPBD) (European Commission, 2021). The new directive focuses on operational energy efficiency of new and existing buildings but also considers whole-life carbon emissions. The life cycle perspective considers both operational and embodied emissions of the building. Efficiency in embodied emissions from materials has shown to have a massive reduction potential (UNEP, 2022). Thus, the design of new construction and renovation in a life cycle perspective is important for a transition towards low-carbon buildings.

The design of building and renovation projects is dependent on the work carried out by actors in the building sector, such as architects and engineers. To effectively reduce emissions, key needs for the actors are 1) a true and fair method for assessing the life cycle based GHGe, and 2) effective ways to integrate the assessment in their design process.

If we first consider 1) on the methods, standards already exists to describe the procedures for documenting GHGe through life cycle assessment (LCA) of buildings (CEN, 2012b). In practice, however, methods can vary, causing different results (Pomponi & Moncaster, 2018; Rasmussen et al., 2018; Röck, Ruschi Mendes Saade, et al., 2019). But harmonizing and unifying methods have also been progressing. Especially following the rapid growth in literature on LCA of buildings and its practical use in certifications (Geng et al., 2017; Skillington et al., 2022). Recently, the development has resulted in several implementations of LCA of buildings in national legislation (OneClickLCA, 2022). Despite this development, renovation projects have not been investigated to the same degree as new construction. This means that data is significantly lacking for LCA of renovation (Anand & Amor, 2017). Method development has predominantly focused on new construction rather than renovation (Hussien et al., 2023). Thus, the methods for performing LCA of renovation vary significantly in literature (Vilches et al., 2017). Renovation projects are more complex as they vary in type, scale, existing conditions, and requirements (Shahi et al., 2020).

Considering 2) the integration in the design process, a major barrier to practical implementation of LCA is the time-consuming and complex work of performing LCA of buildings (Balouktsi et al., 2020; Rasmussen et al., 2020; Soust-Verdaguer et al., 2017). Several LCA tools for performing the assessment are available (Di Bari et al., 2022). However, these tools alone are not enough when the collection of material quantities is considered the most time-consuming task (Meex et al., 2018). Different approaches are available to gain the material quantities, including the use of digital tools such as building information model (BIM) or 3D models (Röck, Passer, et al., 2019). However, there are still many challenges related to the integration process of LCA tools and the 3D building models used in the industry (Tajda Potro Obrecht et al., 2020; Röck, Passer, et al., 2019; Soust-Verdaguer et al., 2017)

Thus, methods for renovation and tools for better integration in the design process need to be developed to support actors from the buildings sector in the design of low carbon building and renovation projects.

1.2. RESEARCH AIM-, FOCUS-, AND QUESTIONS

To solve the climate challenge of buildings, it is necessary to consider not only new construction but also the large existing building stock. This requires an investigation of the LCA-method applied for renovation projects, including the benchmarks used to evaluate them. Furthermore, the practical implementation of LCA in the design process needs to be investigated to optimize the design.

The aim of the dissertation is to identify and evaluate, for future method development and policymaking, significant methodological variations and challenges in relation to performing and benchmarking LCA of renovation and suggest how methods and benchmarks can be implemented in practice. Furthermore, the dissertation aims to identify needs for future development of digital tools to integrate LCA in the design process and develop practical approaches.

The dissertation has a dual focus on *method and benchmark in renovation* and the *integration in design process*, see figure 1-1. For LCA of renovation, method approaches, and benchmarks are investigated, together with their influence on how easy they are to integrate in the design process. For the design process, existing approaches for integrating digital tools to perform LCA are investigated, and new practical approaches to assess renovation projects in the design process are developed.

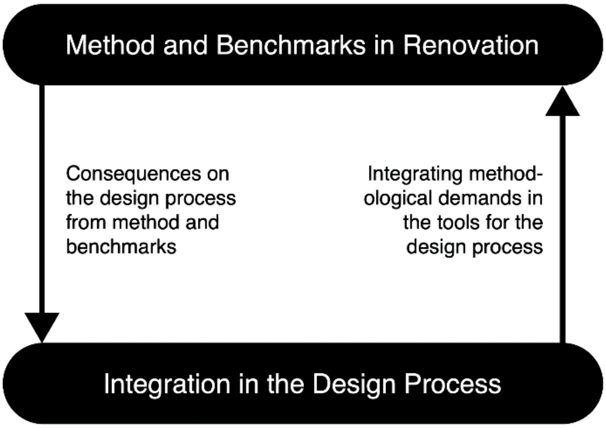


Figure 1-1 The dual focus in the PhD dissertation

The overall research question (RQ) in the dissertation is

RQ: **How can LCA for the building industry be developed within the topics of renovation and digital tools for the design process to reduce GHG emissions of buildings?**

There are five sub-questions (SQ) that pertain to the main research question:

Renovation (method and benchmark):

SQ1: What are GHG emissions from real-life renovation cases?

SQ2: What are design incentives from different methodological approaches?

SQ3: What method-related aspects should be considered when benchmarking renovation?

Integration of LCA in the design process:

SQ4: How can LCA of renovation be implemented in practice?

SQ5: What are the current approaches and challenges within the integration of the building model and LCA tools?

1.3. CONTEXT: THE PHD WORK AS PART OF NATIONAL TOOL DEVELOPMENT STRATEGIES

The PhD work is part of a larger project connected to the future development of the Danish tool for performing LCA on buildings, LCAbyg. The project focuses on LCA of renovation and tool integration. Figure 1-2 shows the contribution of the PhD work to the identified development areas within LCAbyg. The PhD work performs the initial analysis within the two selected development areas. These analyses are focused on the direction of the development in LCAbyg, whereas the later work will include the integration into LCAbyg.

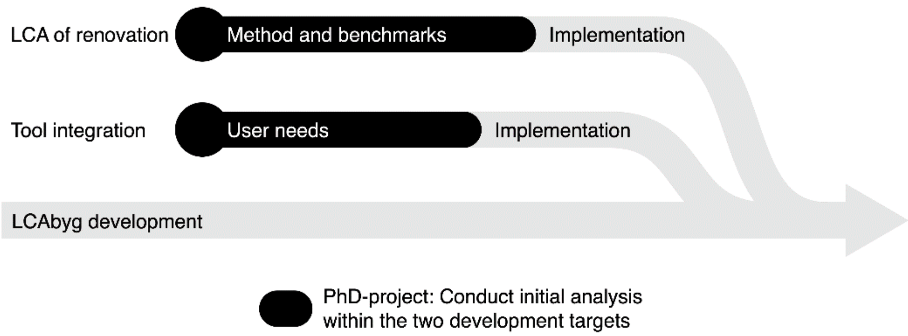


Figure 1-2 The PhD work performs the initial analysis in a larger development project of LCAbyg focused on renovation and tool integration

LCAbyg is a free tool from 2015, which was developed to perform LCA on buildings for the Danish context. The target audience of the tool is consultants in the building industry, such as architects, engineers, and other stakeholders, who are not necessarily experts within the field of LCA. Thus, the tool is developed to comply with the European standard for LCA of buildings, EN 15978, and the usability of the target audience. LCAbyg is currently used in sustainable building certification schemes, such as the Danish version of DGNB (Rådet for bæredygtigt byggeri, 2023). Furthermore, it can be used to comply with the Danish regulatory demands for LCA on buildings, which became effective in 2023 (Danish housing and planning authority, 2023).

The development of LCAbyg initially started in 2014. The development of the tool happened in collaboration with authorities and an advisory council representing future users and interested parties (Kanafani et al., 2021). Since then, expert sessions and workshops have continuously tested and given input to the development. The two key development areas were identified to support the future usability of LCAbyg based on user input. The two are: supporting LCA of renovation projects and the integration between building models and LCA calculation tools. Up until the start of the PhD work, the primary focus of the tool and its development was new constructions, as this was the most common use for LCA. In practice, renovation projects were assessed (and certified) following a similar approach as new construction, including identical benchmarks, without considering the significant differences in function, material use etc. However, with the continued assimilation of LCA in the building sector, this gap in knowledge for renovation has become evident. Furthermore, the industry also calls for solutions to enhance the efficiency of the process, such as the use of 3D or BIM models for performing the LCA. For LCA on renovation, investigations for this PhD work focus on implications of the choice of method and benchmark in renovation. For the tool integration, the initial analysis is focused on implementation from a user perspective, as opposed to existing literature, which focuses mainly on the development of technical solutions.

1.4. READER'S GUIDE

1.4.1. PUBLICATIONS AND THEIR RELATION TO FOCUS

The following academic publications represent the analytical work carried out to address the research questions presented in the previous section:

Publication I: **Whole life GHG emissions from 23 building renovation cases – contributions from energy reduction versus other renovation actions.** Zimmermann, R. K., Rasmussen, F. N., & Birgisdottir, H. Submitted to Energy & Buildings, 2023

Publication II: **GHG emissions from building renovation versus new-build: incentives from assessment methods**. Zimmermann, R. K., Barjot, Z., Rasmussen, F. N., Malmqvist, T., Kuittinen, M., & Birgisdottir, H. In Buildings and Cities, 2023, 4 (1), pp 274-291

Publication III: **Reviewing allocation approaches and modelling in LCA for building refurbishment**. Zimmermann, R. K., Rasmussen, F. N., Kanafani, K., Eberhardt, L. C. M. & Birgisdottir, H. In: IOP Conference Series: Earth and Environmental Science, 2022, 1078

Publication IV: **Automated Life cycle inventories for existing buildings – a parametric reference model approach**. Kanafani, K., Garnow, A., Zimmermann, R. K., Sørensen, C. G., Brisson Stapel, E. & Birgisdottir, H. In: IOP Conference Series: Earth and Environmental Science, 2022, 1078

Publication V: **BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs**. Zimmermann, R.K.; Bruhn, S.; Birgisdóttir, H. In: Sustainability, 2021, 13 (10) no. 5455

Figure 1-3 shows how the publications are related to the dual focus within the dissertation. On the left-hand side of the figure, Publication I, II, and III analyze different aspects of the LCA-method and benchmark used for renovation projects, considering the functions provided in renovation, the allocation of existing materials, life-cycle stages, etc. Furthermore, the publication also considers the practical consequences on the design process of the methodological approaches, such as incentives and workload related to the use of different LCA approaches.

The definition of renovation in general and for the use in LCA can be very wide. For the purpose of this dissertation, the word "renovation" is used as an umbrella term for all changes to the existing building. However, for the PhD work carried out, the majority of case studies considered are major renovations and/or large-scale refurbishments in line with the definitions presented in section 2.2.1.

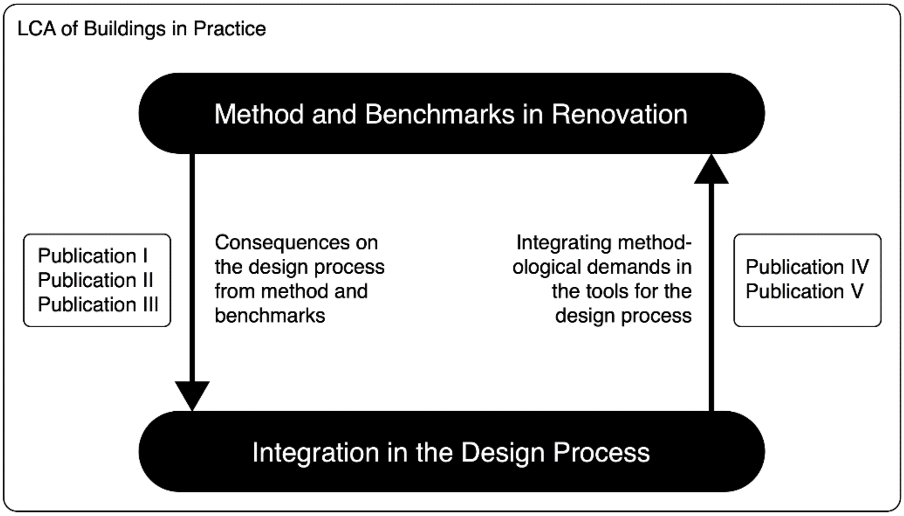


Figure 1-3 Main topics in the dissertation and their links to publications.

On the right-hand side of the figure are Publication IV and V. These publications analyze and propose ways to implement LCA in the design process. This includes simplified approaches for early design, efficiency from BIM-LCA, and integrations in the national tool, LCAbyg. The implementation strategies also try to solve demands from the method, such as the inventory for including existing materials in renovation projects.

All analyses are considered within the perspective of the practical implementation of LCA in the buildings sector, which is illustrated by the surrounding box in figure 1-3. This means that the performance of LCA of buildings should be possible for practitioners in the building industry who are not LCA experts. Furthermore, the assessment should follow a standardized procedure to comply with the need in certification schemes and regulations.

1.4.2. METHODS USED IN THE PUBLICATIONS

The publications use different approaches to analyze the topics of implementation and method and benchmark in renovation. Table 1-1 shows the use of methods in the different publications. The methods are described in chapter 3.

Table 1-1 Methods used in the different approaches

Methods	*Pub I*	*Pub II*	*Pub III*	*Pub IV*	*Pub V*
LCA	X	X			
Case study	X	X		X	
Interview					X
Review			X		
Parametric model development				X	

1.4.3. STRUCTURE OF THE DISSERTATION

The dissertation is structured into six chapters. The present chapter presents an overview of the themes and work carried out and presents the scientific contributions. Chapter 2 presents the state-of-the-art within LCA on buildings and strategies for practical integration in the design process. Chapter 3 explains the methods used in the research in the publications. Chapter 4 presents the findings from the work carried out in the PhD, in relation to the main topics presented in figure 1-2: *Method and benchmark in renovation* and *Integration in design process*. Additional outlooks are given in the discussion in Chapter 5, which contribute to the conclusion and future research presented in Chapter 6.

For chapters 2, 4, and 5 (*State-of-the-art*, *Findings*, and *Discussion*) a summary is provided, which allows for a quick reading of the dissertation.

1.5. MAIN CONTRIBUTIONS

The main empirical contributions and contributions to policy and practice are listed below.

Empirical contribution:

- GHG emissions of 23 renovation cases, and the contribution from different added functions in renovation projects.
- GHG emissions from renovation versus new construction using the Danish, Swedish, and Finnish LCA-approaches.
- Mapping of allocation and modeling approaches in LCA of renovation
- Current BIM-LCA integration approaches and challenges in Danish consulting companies.

Contribution to policy or practice

- Identification of incentives from different national LCA-based climate declarations for renovation versus new construction
- Mapping of practical consequences of different allocation approaches for existing building materials
- Evaluation of suggested renovation benchmarks based on a collection of real-life renovation cases
- Reflection on possibilities of how to implement LCA of renovation as a consequence of the coming energy performance of buildings directive (EPBD)
- Development of an automated approach to create inventory of the existing building for LCA of renovation
- Identification of needs in BIM-LCA

CHAPTER 2. STATE-OF-THE-ART

This chapter will give a general overview of the state-of-the-art relevant to the research topics presented in Chapter 1.

2.1. LCA OF BUILDINGS IN PRACTICE

To assess the environmental performance of buildings, a life cycle assessment (LCA) can be applied. The method is science-based and considers a life cycle perspective as well as the assessment of several environmental issues to avoid burden shifting (Hauschild et al., 2018). The general methods to perform LCA of products and services are standardized in the ISO 14040 and 14044 standards (ISO, 2006a, 2006b). For assessments targeting buildings, specifically, the procedure for LCA is standardized through the European standard, EN 15978 (CEN, 2012b), and for building products in EN 15804 (CEN, 2019). The latter defines the method for environmental product declarations (EPD's) for construction products. The EU standard for buildings and construction products is based on the ISO standards (ISO/TC 59/SC 17, 2002), where the modular approach used in Table 2-1 was also introduced.

Table 2-1 The life cycle stages and modules of a building. Adapted from EN 15978 (CEN, 2012b)

Product stage			Construction process stage		Use stage							End of life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Construction, installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction, demolition	Transport	Waste processing	Disposal	Reuse-, Recovery-, Recycling potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D

While the standardization for LCA of buildings provide harmonization of overall method and terminology, it still allows for different interpretations in relation to included life cycle stages, environmental data, reference study period, etc., that affect the outcome of the LCA (Nwodo & Anumba, 2019; Rasmussen, 2020). National approaches and certification schemes contribute to the variety in scope but also contribute to the growing use of LCA of buildings: The number of publications related to LCA of buildings is rapidly growing in literature (Geng et al., 2017). Further, LCA of buildings is also growing for voluntary certification (Skillington et al., 2022), and in national regulations, where climate declarations of buildings based on a life cycle approach were first introduced in the Netherlands (Scholten & van Ewijk, 2013). Recently, it has been introduced in a number of European countries, such as France, Sweden, Denmark, and Finland (OneClickLCA, 2022). For this purpose, each country has defined country-specific methods based on EN 15978. These methodological choices are influenced by preconditions of industry practices, as well as ease of application (Rasmussen & Birgisdóttir, 2016). *Ease of application* shows the influence of the socio-technical reality, where comprehensiveness is sometimes compromised due to the needs of the actors using the system in practice (Rasmussen et al., 2019).

The definition of national approaches is often followed by a statistical analysis considering the current performance of new construction in the countries (Malmqvist et al., 2023; Zimmermann, Andersen, et al., 2021). These reference values can be used as benchmarks for new construction, following guidelines in the standard for benchmarks, ISO 21678 (ISO, 2021). The benchmarks can be used in a policy context to set limit values in regulation, specifying the minimum performance requirements of buildings (Lützkendorf & Balouktsi, 2023). However, building renovation typically lacks behind in this development. Anand and Amor (2017) mention the lack of data on renovation analyses as one of the key challenges in LCA of buildings, with the need for more research on the whole building level and more case studies to create reference points. Supplementary to benchmarking the life cycle perspective, a key concern is to limit the *upfront* emissions from material production, transport, and construction processes (Röck, Ruschi Mendes Saade, et al., 2019). Upfront emissions are important to address the immediate need to cut GHGe to keep the global temperature rise at 1.5˚C (IPCC, 2023). Further, the focus on benchmarks in regulation highlights the issue in relation to the functional unit and whether this can be compared across different building projects. Here, Erlandsson and Borg (2003) argue that LCAs for different buildings are not comparable because every building project is unique in location and functional qualities.

2.2. LCA OF RENOVATION

2.2.1. FUNCTIONAL QUALITIES IN RENOVATION

In literature and practice, *renovation* is used interchangeably with refurbishment, retrofitting, conversion, etc. (Shahi et al., 2020). Based on a literature review of terminology, Shahi et al. (2020) define two overall categories for building adaption: Refurbishment and adaptive reuse. The first focuses on improvements to the building, including energy efficiency, structure, interior design, occupant comfort, etc., while the latter focuses on changing the function of the building and reuse of building materials. A project can consist of any combination of these. Thus, renovation projects consider a large range of scale and include several different improvements to the building.

The building envelope is part of the focus of the European Energy Performance of Buildings Directive (EPBD) (European Commission, 2021) and the European framework for sustainable buildings, Level(s) (Dodd et al., 2021). Here, they use the term “major renovation”, which can be defined based on a minimum cost or a minimum surface area that is renovated. Thus focusing on the size of changes in either a monetary or building envelope scale. The focus on building envelope considers an energy efficiency perspective. The attention on “energy retrofit” is also visible in existing literature on LCA of renovation, where different energy retrofitting actions are typically carried out (Hussien et al., 2023; Vilches et al., 2017). These actions include increase of insulation in walls and roofs, followed by replacing windows, improving energy efficiency of air conditioning units, and installing PV panels (Vilches et al., 2017). In the assessments, the retrofitting scenario can be compared with a “no intervention” scenario to calculate the performance and possibly the “payback period” of retrofitting. Energy retrofitting typically performs well for the environmental indicators assessed (ibid). However, the inclusion of other impacts from e.g. the interior changes could increase the quality of the LCA (Ghose et al., 2017). Office building fit-outs have, for instance, shown to contribute with between 12-15% of initial embodied impacts (ibid.)

Energy efficiency is not the main focus in an upcoming European standard prEN 17680 on the sustainability of refurbishments (CEN, 2021b). In the standard, a refurbishment is also considered large scale but can be defined by a change of space plan or a change of the function of the building. Thus, the definition also focuses on internal changes and adapting the use of the building. This definition is repeated in the updated draft of EN 15978 for the environmental performance of buildings, with emphasis on projects where changes happen in the functional equivalent, such as the change of building type or a change in the required service life (CEN, 2021a).

The definition of renovation in general and for the use in LCA can thus be very wide, but in literature and legislation on the environmental performance of buildings, it has commonly been used to consider energy retrofit actions.

2.2.2. SYSTEM BOUNDARIES FOR LCA OF RENOVATION

The EN 15978 standard defines renovation as part of the use stage in the building life cycle through the “refurbishment” module B5 (see table 2-1). This module considers the EoL of replaced building materials, the production of new materials, as well as transport and construction processes. Module B5 is scenario-based because it is defined as a future occurrence. However, the EN 15978 standard is intended for both “new and existing buildings”. The standard specifies that if the object of assessment is an existing building that is renovated and no previous LCA for the building exists, a new LCA should be made. The impacts from materials and installation processes from the renovation actions are then allocated to module A1-A5. When renovation actions are allocated to the initial product stage, the life cycle of the building is effectively divided into two life cycles: one before and one after renovation, see figure 2-1.

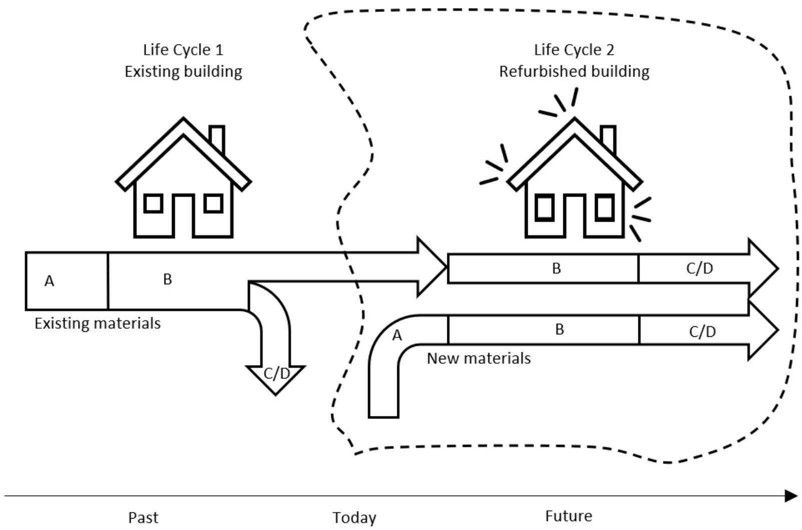


Figure 2-1 System boundaries for renovation projects (in figure called "refurbishment") can vary. The letters refer to the life cycle stages in EN 15978. From publication III (Zimmermann et al., 2022)

When the building's life cycle is divided into two consecutive life cycles, it becomes necessary to define the system boundaries, especially how to consider the existing materials (Obrecht, Jordan, Legat, Mendes Saade, et al., 2021). A consequential approach will not consider past emissions but only those that will happen as a consequence of the decision (Huuhka et al., 2023). However, attributional approaches use several approaches, including allocating part of the production of existing material to the renovation projects (Obrecht, Jordan, Legat, Mendes Saade, et al., 2021). Using allocation, the emissions from already produced materials can even be adjusted to fit previous production (Obrecht, Jordan, Legat, & Passer, 2021). However, the cut-off approach is applied in EN 15978 and 15804, which form the basis of the current European practice for LCA of buildings and products. This approach focuses on current emissions, and the material production of products is entirely allocated to the first life cycle (Frischknecht, 2010).

Despite the standardized method and use of cut-off approach, approaches can still differ. In a review of LCA of renovation by Vilches et al. (2017), there was a large difference in the investigated studies of how the existing building was included in the LCA of renovation, and only few of the studies included impacts from existing materials. Similar conclusions were made in a review of life cycle sustainability assessment on building energy retrofitting, where EoL is commonly excluded (Amini Toosi et al., 2020). The EoL processes from existing building materials are sometimes omitted due to their assumed insignificant emissions(ibid.).

2.3. INTEGRATION IN DESIGN PROCESS

The complexity and time consuming work related to performing LCA on building is considered a barrier to its use in the design process (Balouktsi et al., 2020; F. N. Rasmussen et al., 2020; Soust-Verdaguer et al., 2017). Integrating LCA in the design process is vital to reducing GHGe, as it is generally recognized that the early design stages of the building can have the largest influence on reducing environmental impacts (Basbagill et al., 2013; Marsh et al., 2018; Meex et al., 2018). To ease the implementation, practitioners in the building sector use a simplified approach for the scope of the assessment in LCA of building, such as only considering a limited amount of life cycle stages, building elements, etc. (Beemsterboer et al., 2020; De Wolf et al., 2017). This is identical to the simplifications used in national approaches that, beyond considering preconditions for the national context, have also adjusted to the “ease of use” for the practitioner (Rasmussen et al., 2019). Though the simplifications may reduce the reliability of results, they encourage the use of LCA in the building design due to easier implementation (Anand & Amor, 2017). Different methods can be applied for selective simplification strategies to support the credibility of results (John, 2012; Wittstock et al., 2012).

Other approaches to increase the “ease of use” for practitioners include tools and libraries. Tools that consider the simplified LCA scope of one or more contexts include LCAbyg for the Danish context (Kanafani et al., 2021), eLCA for the German context (Federal Institute for Research on Building, 2014), OneClickLCA includes several contexts (Bionova Ltd, n.d.), and a number of other examples presented by Di Bari et al. (Di Bari et al., 2022). The LCA-tools help the user perform a simple and unified approach that applies to e.g. a national context. However, the bill of material quantities is generally considered the most time consuming task in the process of performing LCA of buildings (Meex et al., 2018). Therefore, a comprehensive library including materials and building components is suggested by Meex et al. (ibid.). Here, default values can be used to substitute the unknown data until it becomes available, such as using default values for building components (Marsh, 2016). For the Danish tool, LCAbyg, a generic library was also introduced with building components, along with a model to help estimate the building geometry based on simple available information on the building, such as ground floor area and number of floors (Kanafani et al., 2019; Zimmermann et al., 2019). Libraries and tools, however, are typically aimed toward new construction, thus the “ease of use” for renovation projects is neglected. This is even though information on materials and quantities is not as easily available for existing buildings. For instance, building information modeling (BIM) is limited for existing buildings due to the high effort required to create BIM for existing buildings (Volk et al., 2014).

BIM or 3D model of the building can also be used to get the building geometry and quantities for the LCA, when available (Meex et al., 2018). For early design stages, information from 3D models or (BIM), can be combined with predefined components when the material quantities are not known (Cavalliere et al., 2019; Röck et al., 2018). The use of BIM to perform LCA has gained attention in literature due to its efficiency potential (Fonseca Arenas & Shafique, 2023; Obrecht et al., 2020; Soust-Verdaguer et al., 2017). Information from the BIM (or 3D model) can be transferred into a dedicated LCA-tool, thus eliminating the need to reenter information that is already available in the model. However, the methods often lack user-friendly platforms to assist the integration between BIM and LCA-tools, and considerations of interoperability between tools (Soust-Verdaguer et al., 2017). Interoperability in BIM-LCA can be achieved through the use of e.g, industry foundation classes (IFC) (Figl et al., 2019; Horn et al., 2020; Laakso & Kiviniemi, 2012; Santos et al., 2019; Theißen et al., 2020). For public procurement, an EU directive promotes the use of BIM, and submissions can be required in the form of IFC (Directive 2014/24/EU, 2014). Some literature has also focused on user-friendliness by visualizing data though the 3D model (Kiss et al., 2019; Röck et al., 2018; Tsikos & Negendahl, 2017), and in tools, such as EveBIM and 6D-BIM-Terminal (CSTB, n.d.; Figl et al., 2019).

Different approaches exist for a BIM-LCA integration. Literature distinguishes between extracting information from the BIM, e.g. a “quantity take-off”, and approaches where environmental information is added to the model “enriched BIM” (Antón & Díaz, 2014; Díaz & Antön, 2014). The latter approach reduces the work in the integration process with an LCA-tool, because the information already exists in the model, thus supporting an automatic or semi-automatic workflow for the integration process (Santos et al., 2019). It can furthermore be used in early design stages to evaluate solutions (LLatas et al., 2022). However, this process requires establishing where information should be stored in the model and how to exchange it. The most common approach in literature is the quantity take-off approach. For this approach, the processes can be both manual and automatic, though the inclusion of some manual processes is the most common (Obrecht et al., 2020).

2.4. SUMMARY OF STATE-OF-THE-ART

Life cycle assessment (LCA) is a science-based method that quantifies the potential impacts on environmental issues. For buildings, LCA is standardized through the European standard, EN 15978. While this standard provides harmonization of overall method and terminology, it still allows for different interpretations in relation to included life cycle stages, environmental data, reference study period, etc. Country-specific interpretations based on the EN 15978 standard have recently formed the basis of several national regulations on LCA of buildings. To assess the performance of buildings, benchmark values can be created, which can act as limit values in legislation. However, benchmarks typically assume comparability across building projects. This can be debated due to buildings' unique functional qualities, especially considering renovation projects. Other than being complex, renovation projects are also less covered in literature and legislation.

Renovation is used interchangeably in literature and practice covering improvements to the building, such as energy efficiency, structure, interior design, occupant comfort, change of function, etc. In European legislation and standardization of sustainability and environmental assessment of buildings, the definitions encompass e.g., changes of use, large costs, large changes in the building envelope, or changes in interior layout. Despite the variety of renovation projects, the literature on LCA of renovation mainly considers "energy retrofitting", covering renovation actions to reduce operational energy.

Performing LCA on a renovation project effectively splits the building life cycle into "before" and "after" the renovation. This leads to considerations on how to allocate existing materials in the renovation. In literature, this is dealt with in different ways.

For the integration of LCA in the design process of new construction and renovation projects, the key barrier to performing LCA is the complex and time-consuming work. Simplified scopes are, therefore already implemented in national approaches, where dedicated tools help with the work. Libraries with materials and components are another way to help with the time-consuming task of collecting the material quantities. Further, building information models (BIM) or 3D models can also be used to determine quantities. However, user-friendly platforms to assist this process are often missing.

CHAPTER 3. METHOD

This chapter explains and justifies the methods chosen for the work presented in this dissertation. In the Reader's Guide in Chapter 1, Table 1-1 shows an overview of which methods are used in the individual papers.

3.1. CASE STUDIES

A case study is an empirical method that allows us to investigate the case while retaining a holistic, real-world perspective (Yin, 2018). Case studies are therefore particularly relevant when we assume there are important real-world contextual conditions at play (ibid.). The use of case studies is common within the research field of LCA of buildings (Ruuska, 2018). For new buildings and especially renovation projects, the contextual conditions can be considered unique in relation to their location, building type, technical requirements, user-specific requirements, etc. (Erlandsson & Borg, 2003; Goldstein & Rasmussen, 2018). For the PhD work, case studies are therefore used to consider these real-world contextual conditions affecting the LCA of buildings. This real-world perspective is important to gain knowledge on the actual impact of building projects. Further, it is also important to consider these contextual differences in the practical application of LCA in the building sector, and particularly in relation to policy and legislation.

The case studies used in the PhD work are either single case studies or multiple-case studies. In Publication I multiple-case studies are analysed to illustrate and quantify the variety of GHG emissions of different construction work in renovation cases. For the study, the selection of cases is random; however, the samples are stratified according to the definition by Flyvbjerg (Flyvbjerg, 2011). This means that they represent a subgroup within the population of renovation cases. Random selection of cases avoids bias, however, the use for generalization is dependent on the sample size (ibid.). While the sample size in the study is large compared to previous studies, generalization is still limited due to the unique quality of the projects. However, the purpose of the study is not to generalize but to illustrate real-world emissions and indicate possible trends. Case studies are also used in Publications II and IV. The choice of cases in these publications is based on an information-oriented selection, meaning that the cases are selected based on expectations of their information content (Flyvbjerg, 2011). Publication II analyses a renovation case of a typical building typology using different national LCA approaches. Thus showcasing the impact of the different methods on a typical real-life case. In Publication IV a selection of cases within a specific building typology is used to create a library of existing building materials and a parametric model. The purpose is to be able to create an inventory of an existing building, but only for the specific building typology.

3.2. LIFE CYCLE ASSESSMENT – A HARMONIZED PROCEDURE

Life cycle assessment is used to quantify the potential GHGe for the case studies in Publication I and II. For both publications, the work was carried out using nationally harmonized LCA approaches following the EN 15978 standard. The author of this dissertation has participated in ongoing work on the use of harmonized Danish LCA approaches in LCA tools for the building industry, which has been documented in several publications (Kanafani et al., 2019, 2021; Zimmermann et al., 2019). However, national approaches are still mainly targeted towards new construction. Therefore, Publication I and II investigate implications related to method and benchmarking for renovation in nationally harmonized LCA approaches, which is still under development. Publication I uses the Danish approach, whereas Publication II consists of both Danish, Swedish, and Finnish approaches. Therefore, the following will summarize the Danish approach using the reporting structure of EN 15978 and highlight some of the main differences from the other national approaches. The development of approaches in the countries is ongoing, and the methods used for the PhD work therefore reflect the practice at the time. More detailed information on the Swedish and Finnish approaches can be found in publication II and in the official documentation (Ministry of the Environment, 2022; The Swedish Parliament, 2021).

3.2.1. PURPOSE OF ASSESSMENT

The goal and intended use of the study vary in the two publications. In publication II, the goal was to assess the performance of renovation versus demolition and new construction using three different national LCA approaches. The intended use was to highlight method-related aspects for future development of methods. For publication I, the goal was to assess GHGe from changed function in a larger sample of real-life renovation cases in a Danish context. The intended use is to contribute to the discussions on method development and benchmarking for renovation projects.

3.2.2. OBJECT OF ASSESSMENT

The object of assessment in all publications, is a renovated building. The renovated buildings are compared through a functional equivalent, which is expressed through a common reference unit. The reference unit used in the Danish approach is the global warming potential per m^2 per year, with reference to the gross floor area of the building, and a reference study period (RSP) of 50 years. For the comparison of renovation against new construction, both scenarios use the same reference study period (of 50 years) as recommended in literature (Decorte et al., 2022). In Publication II, the reference units differ for the other national approaches. Therefore, it was chosen to present the results in this publication without the dimension of per m^2 per year, to be able to compare the global warming potential from different national modeling approaches. The building type in Publication II is residential, while in Publication I, the building cases are a mixture of different building types, though mostly residential, followed by office buildings, institutions etc.

3.2.3. BOUNDARIES AND SCENARIOS

The system boundaries follow the practice from national approaches. In the publications, the system boundaries for the Danish approach include the following life cycle stages and modules from EN 15978: Product stage (A1-A3), replacements (B4), operational energy use (B6), waste processing (C3), and disposal (C4). In Publication II, benefits and loads beyond the system boundaries (D) are also illustrated in some of the figures. This was mainly to show benefits from existing material (i.e. materials that are either removed or retained in the building at the time of renovation), specifically the removed materials that contribute to upfront benefits. The included life cycle stages from the Swedish and Finnish approaches vary from the Danish (see table 1 in publication II for specific differences). Most notably, the Swedish approach only considers upfront emissions (modules A1-A5).

Publication II also investigated the inclusion of existing materials in the assessment of renovation against demolition and new construction. The inclusions of existing materials differ in the national approaches, which reflects the varied inclusion of existing materials in assessments of renovation in scientific literature (Decorte et al., 2022). The Danish and Finnish approaches include existing materials in replacements and EoL modules. Existing materials are not included in the Swedish approach. See publication II for a detailed description of the system boundaries and modeling. In Publication I, only new materials are considered for the assessment of added functions.

The replacement module (B4) includes production of a new material and waste processing and disposal of the removed materials. The replacements are determined by the service lives of the materials from Haugbølle et al. (2021). The approach is similar in Finland but using different service lives (Finnish Environment Institute, 2023). Scenarios for the EoL processes follow the generic datasets, explained in the following sections. For the energy use, a projected approach is used, which models politically set targets for the decarbonization of the energy grid. The modeling introduces more renewable energy carriers for district heating and electricity (COWI, 2020; Danish Energy Agency, 2021). A similar decarbonization modeling is used in the Finnish approach (Finnish Environment Institute, 2023).

3.2.4. BUILDING MODEL DESCRIPTION

The inventory of the case buildings in Publication II and I consists of foundations, ground floor slab, external walls, roofs, windows and doors, internal walls, floor decks, stairs and ramps, columns and beams, balconies, building services (water, ventilation, heating and cooling). The assessment also includes finishings. For the operational energy use, the demand regulated in the Danish building regulations is included. This consists of energy from heating, cooling, ventilation, hot water, and lighting (Danish housing and planning authority, 2023). For the other national approaches, transport distances and construction processes have been included as described in Publication II.

3.2.5. ENVIRONMENTAL DATA AND INDICATORS

To assess the potential environmental impact of materials and processes, the database from the tool LCAbyg was used and supplemented with EPD's from specific products. Data from LCAbyg represents the Danish approach used in Publication I and II, whereas the national approaches in Sweden and Finland use their own databases (Boverket, 2022; Finnish Environment Institute, 2023). LCAbyg uses a database that consists of generic data from the German Ökobau database (Ökobaudat, 2023), and average EPD's representing the Danish context. Data from both Ökobaudat and EPD's follow the EN15804 standard (CEN, 2012a). The generic data from Ökobaudat is based on background data from Sphera (formerly Thinkstep) (Sphera, 2023), whereas the EPD's can be from different background databases. The potential environmental impact is reported at midpoint using characterisation factors from CML-IA database following the EN 15804:2012+A1 standard. The GHGe's impact on climate change is reported by the indicator "global warming potential" (GWP) for a 100-year time horizon and measured in kg CO_2 equivalents (kg CO_2-eq). For operational energy use a decarbonisation scenario is used as specified in the description of scenarios, where the modelling of emissions take into account the increase of renewable energy in the grid (COWI, 2020; Danish Energy Agency, 2021).

3.2.6. SENSITIVITY

Uncertainty and sensitivity management can be used to improve a study's precision and the robustness of conclusions (Hauschild et al., 2018). While uncertainty describes how much we may be off from the truth (ibid), sensitivity analysis is a "systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study" (ISO, 2006a). For the purpose of this PhD study, which uses harmonized LCA approaches for renovation, the effect of modeling choices on results is of specific interest. The sensitivity of modeling choices and input parameters in LCA can be evaluated by the degree to which their variation leads to a variation in the results (Hauschild et al., 2018). For Publication II, the results of different modeling choices in the national approaches were compared. The publication has a focus on the scope of specifically the life cycle stages, which varied significantly between the approaches. Publication I also analyses the variation of scope but focuses on the completeness of the building inventory. With the large focus on energy renovation actions, it considers how much results are affected if only energy renovation actions are included in the assessment versus the inclusion of other functions.

3.3. INTERVIEW

Qualitative interviews are effective to learn about new topics where limited or no previous theory exists and to understand how a process unfolds (Edmondson & Mcmanus, 2007). Integration of BIM-LCA is a research topic that is developing fast, but where theory is still limited (Obrecht et al., 2020). In Publication V, qualitative in-depth semi-structured interviews were conducted with informants from companies that perform LCA on buildings. The interviews were analyzed and categorized using a combination of deductive and inductive coding techniques (Ligurgo et al., 2018). The deductive coding technique uses the theoretical background of the topic for the coding, while the inductive technique uses emerging themes (Brinkmann, 2013). The purpose of the deductive coding technique was to understand the workflow in the companies in relation to existing literature in the field, such as the classification of typical BIM-LCA integration approaches (see figure 2 in Publication V). At the same time, the inductive coding technique was used to include themes from open discussions related to challenges and needs in the development of BIM-LCA from the practitioner's point of view.

3.4. LITERATURE REVIEW

The literature review is a research method that synthesizes existing literature in a systematic way (Snyder, 2019). Reviewing is used in all publications of this PhD study to position the work within the existing literature, as it provides at theoretical foundation for the study, as well as identifies research gaps (Paré & Kitsiou, 2017). In Publication III, the review forms a large part of the results and analysis. The study creates a research synthesis of existing allocation approaches and modeling in LCA of renovation. A research synthesis requires a purposeful selection and analysis of primary research reports on a similar topic and produces and creates new knowledge by connection individual study reports (Suri, 2011). Snyder (2019) identifies three overall approaches to a literature review: Systematic, semi-systematic, and integrative. Publication III uses a semi-systematic approach. The goal of this approach is to identify and understand potentially relevant research traditions that are important for the topic studied (ibid.). Furthermore, Snyder (2019) defines four phases in the review process: Design, conduct, analysis, and structuring and writing the review. To conduct the review, a search string was used in Scopus, which was supplemented with the snowball approach to find additional relevant literature. The literature was analyzed based on the emerging topics and themes in the literature. Additionally, the different approaches were categorized and illustrated to communicate the results.

3.5. PARAMETRIC MODEL DEVELOPMENT

Publication IV used a parametric model to create the geometry of the existing buildings. This is used to create the inventory of existing materials. Further, the dimensions can be used to add renovation measures such as insulating the building envelope. The parametric model is based on a specific building typology from 1850-1920, which is used widely across Denmark. The model is based on six different buildings within the building typology and validated by cross-checking with an extensive study on these building types by Engelmark (1983). Drawings of the building were compared to find common typology characteristics relevant to creating the building inventory. These include building depth, floor height, roof type, etc. This information was translated into a generic modular unit, where relationships between the dimensions of the elements are based on user input and the constants defined in the typology study, see figure 3-1.

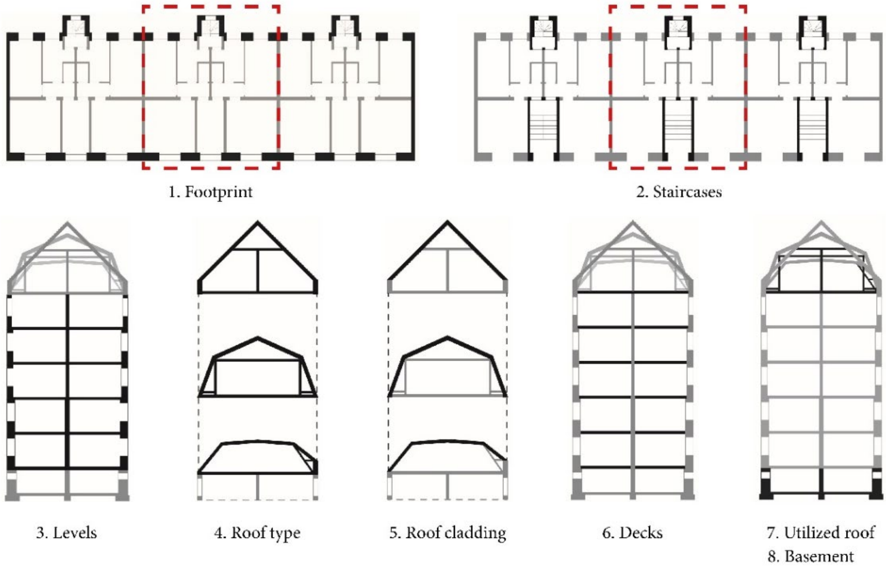


Figure 3-1 Generic modular unit (marked in red) with user defined variations within the building typology (no. 1-8). From publication IV (K. Kanafani et al., 2022)

CHAPTER 4. FINDINGS

The findings presented in this chapter are structured in the two focus areas presented in Chapter 1: *Method and benchmarks in renovation* and *Integration in the design process*. Publications I, II, and III contribute to the method and benchmark, and publications V and IV contribute to practical implementation. The findings from the individual publications are summarized at the end of this chapter.

4.1. METHOD AND BENCHMARK IN RENOVATION

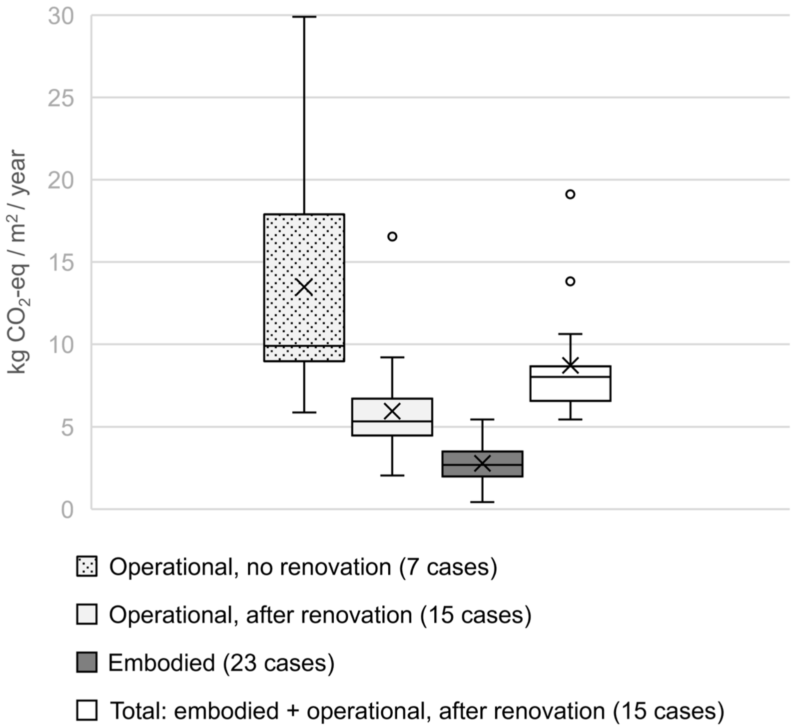
This section addresses the challenges of methods and benchmarks in LCA of renovation in the building sector. The analysis also considers consequences of methods on the practical integration in the design process.

4.1.1. EMBODIED AND OPERATIONAL IMPACTS IN RENOVATION

For LCA on new construction, the contribution from embodied and operational emissions can describe the environmental profile and tendencies, which informs design development for new construction (Röck, Ruschi Mendes Saade, et al., 2019). Similarly, this section aims to characterize renovation projects by their contribution to embodied and operational impact.

In Publication I, LCA has been performed on 23 real-life renovation cases to assess the contribution to GHGe. The cases consist of a variety of building types and renovation measures (See Table 1 in Publication I for more information on the cases and renovation actions). The renovation projects were assessed using the Danish LCA method, considering new materials and operational energy use after the renovation. Furthermore, the operational energy use for the existing conditions (before renovation) was considered for cases where this data was available. This was included to illustrate the savings in operational energy from the renovation measures. The results of the assessment can be seen in Figure 4-1, with individual results for cases in the table. Results show a large variance in the emissions from the cases. The figure illustrates significant operational energy savings of, on average 50% for the 7 available cases, but varying between 20%-65%, due to, for instance, the very different initial energy use and emissions, as illustrated in the figure. The average value for the operational emissions is 6.0 kg CO_2-eq/m^2/year after the renovation. The "investment" in embodied emissions to achieve e.g. operational savings are 2.8 kg CO_2-eq/m^2/year, on average, however, both operational and embodied emission vary significantly across the cases. For the operational emissions, it should be noted that impacts are sensitive to e.g. climatic conditions, energy sources and future scenarios used for the decarbonization of the energy system.

Publication I thus highlights the variance in emissions from renovation projects and the significance of operational emissions in renovation projects, exemplified through the Danish context.



	C1	O1	O2	O3	O4	H1	Hos1	I1	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
⊡				9.9					29.9		17.9		9.0	5.9				9.7		12.1			
□			5.3	3.6			5.2	9.2	16.5		6.8		5.8	4.7	4.5	6.7	4.5	6.2		5.5	2.0	2.7	
■	2.0	5.4	1.2	2.5	1.1	2.8	3.0	4.6	2.6	0.4	3.9	4.2	2.4	2.0	2.0	1.3	2.7	2.2	3.0	3.1	5.1	2.7	3.5
□			6.6	6.1			8.2	13.8	19.1		10.6		8.2	6.7	6.5	8.0	7.2	8.4		8.7	7.1	5.4	

Figure 4-1 Operational and embodied emissions from renovation cases. From publication I (Zimmermann, Rasmussen, et al., 2023)

4.1.2. IMPACTS FROM FUNCTIONAL CHANGES

Section 4.1.1 illustrated the "investment" in embodied emissions against the operational energy savings in renovation projects. But not all of the embodied emissions are related to operational energy reduction. In this section, we therefore analyze the actual functional contributions from the embodied emissions that were shown in figure 4-1.

Publication I has mapped the renovation actions for the 23 cases into the primarily provided function. The mapping was based on functional requirements in the Danish building code (see Table 2 in Publication I for descriptions of the categorization). Figure 4-2a shows the embodied emissions from the cases. The contribution to different functions is illustrated for each of the cases. Further, figure 4-2b shows the spread of emissions from the different functions across cases. The figure shows that *spatial* changes (adding or removing area) and local renewable energy supply (PV-panels) can have high emissions. However, they are not frequent in the case sample. *Spatial* emissions are typically from building extensions that can have a large impact on the results. *Energy reduction* actions appear in most cases and contribute to significant emissions. Other functions that appear frequently across the cases are *layout* changes, followed by *indoor climate*, *balconies*, and *elevators*. *Replacements and repairs* are also frequent but do not add any new functionality to the building.

The energy reduction measures, on average, contribute to 43% of emissions across the cases and 46% when local renewable energy supply is also considered. Subsequently, the remaining 54% of embodied emissions are ascribed to other functions. These results illustrate that if only energy reduction actions are considered for renovation projects, a large part of the embodied emissions will be overlooked. However, the results should be considered in the light of a limited sample of cases and large variety across cases. Most significantly, the results show the uniqueness and variety of renovation projects and their provided functions and indicate key functional contributors. The variety contributes to challenges of e.g. benchmarking renovation of whole projects.

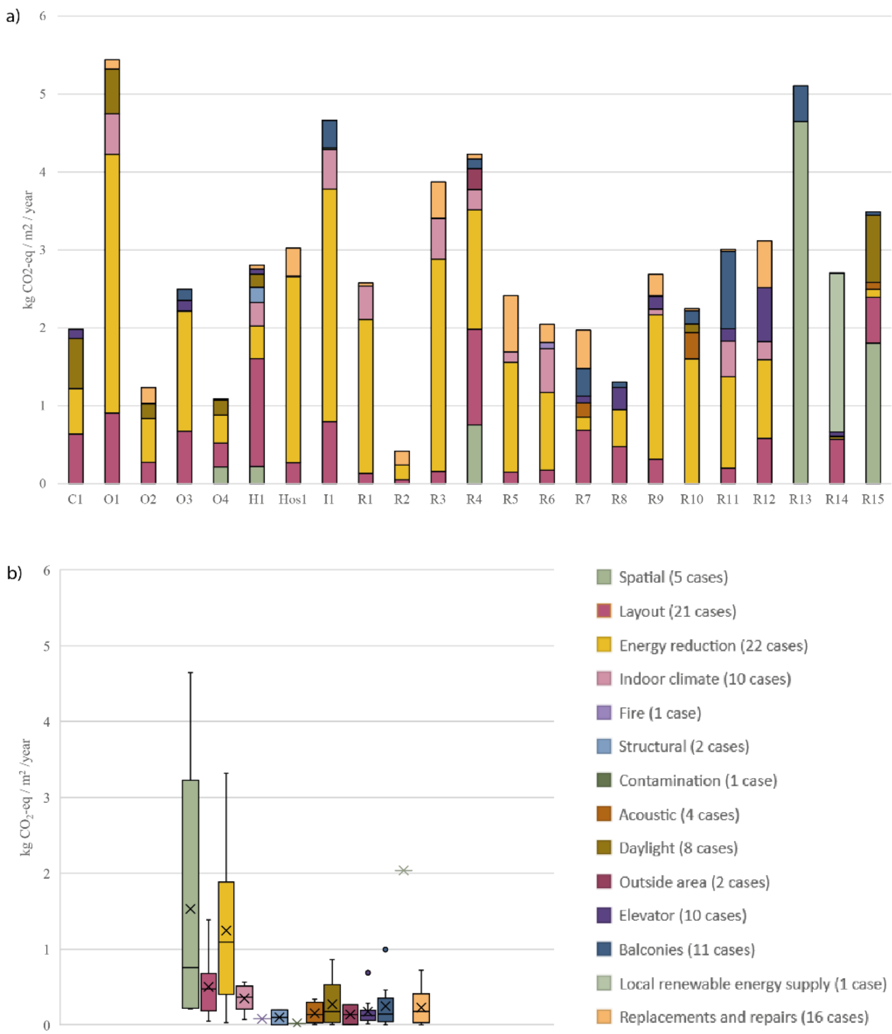


Figure 4-2 Impact from changed functions in renovation. From Publication I (Zimmermann, Rasmussen, et al., 2023)

4.1.3. BENCHMARKING

Based on the assessment of GHGe from a large collection of renovation cases, Publication I reflects on the implication of using previously suggested approaches for benchmarking renovation projects. Publication I has calculated life cycle embodied GHGe on a larger number of renovation cases, as described in section 4.1.1 and 4.1.2.

The suggested benchmarks for renovation projects that were assessed in the publication include "whole building" benchmarks, which is similar to the approaches used today for new construction. Alternatively, benchmarks can be used on a "smaller" scale, such as for elements or components. The trade-off between embodied emissions and operational energy reduction has also been used as a way to evaluate the efficiency of renovation by e.g. using payback time (Vilches et al., 201b). Table 4-1 shows the consideration of these benchmarks based on the results in Publication I. The table, for instance, shows that there can be significant challenges in benchmarking whole buildings due to the unique functional qualities of renovation projects. Thus, benchmarking on a smaller scale, such as building elements or components, can be a viable option.

Table 4-1 Implications of different benchmark types

Benchmark types	**Considerations of benchmarks based on results from Publication I**
Whole building	• Cases had a large variance in embodied and operational GHGe despite most of them being considered "major renovations" according to the EPBD. • The changed functions in renovation differ between projects
Building elements / components:	• The building elements that contribute most to the renovation projects include the elements in the building envelope: Windows and external walls, roof, and ground floor slab. Furthermore, emissions are also significant for building services, internal walls, floor decks, and balconies. • For several of these elements incl. windows and ground floor slabs, it is common that the entire element is replaced. In that sense, it is comparable to element for new construction. However, external walls and roof the renovation actions commonly consists of changes to the existing elements.
Based on operational savings	• Most of embodied emissions do not come from energy reduction activities. This type of benchmark, therefore, only considers the limited part of the embodied emissions that contribute to operational savings.

4.1.4. DIFFERENT METHODOLOGICAL APPROACHES

The approach to perform LCA on renovation varies (Vilches et al., 2017). This section considers some of the significant differences in approaches and their incentives and practical consequences.

Publication II compares the life cycle GHGe of a renovation case with a scenario of demolition and new construction. The renovation case is a multistory residential concrete building from the 1970s. The assessment of the case was carried out using three different national approaches from the Nordic countries. The approaches differed in system boundaries. Both in terms of the included life cycle stages and whether the existing materials in the building were included in the assessment. For the comparison, statistically derived reference values were used, representing the performance of new construction in the countries. For more information on the case and method, see the method section in Publication II. Figure 4-3 shows the comparison of the renovation case to the scenario of demolition and new construction for different countries.

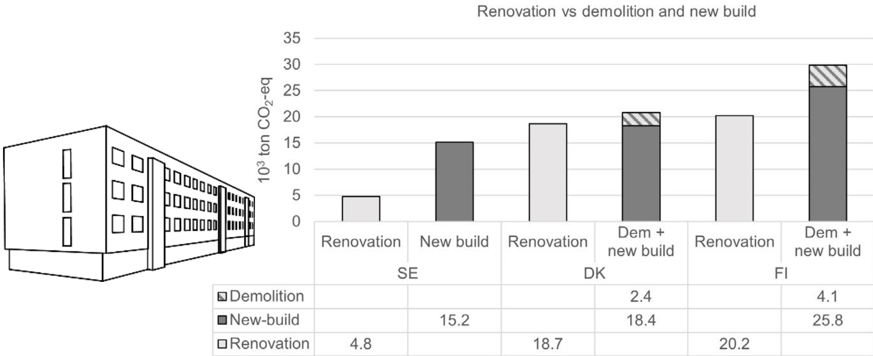


Figure 4-3 Impact from different approaches for LCA of renovation, and compared to new construction. From Publication II (Zimmermann, Barjot, et al., 2023)

Results show that the GHG profile of the identical renovation case varies significantly from using the different national approaches. Moreover, the performance of the renovation project against demolition and new construction varies. This is mainly due to their difference in system boundaries. For the Swedish "SE" approach, only upfront emissions are considered in the assessment, thus, the renovation project performs significantly better than new construction (62% better) due to the difference in material use between renovation and new construction. On the other hand, the Danish "DK" and Finnish "FI" approaches have a much larger GHG profile than the Swedish. This is, in particular, due to the inclusion of operational energy use, see figure 4-4. Consequently, the Danish and Finnish approaches also perform relatively worse compared to new construction (10% and 32% below demolition and new construction, respectively). However, considering the upfront emissions alone, the renovation project has similar emissions for all approaches and performs significantly better than new construction, see figure 4-4. The overall GHG profile of the renovation case is thus very sensitive to the inclusion of operational energy use. However, the influence of operational energy use on the result can potentially negate the significance of upfront emissions if these are not emphasized. The significance of upfront emissions are important in order to stay within a carbon budget, which keeps the global temperature rise to well below 2 ˚C.

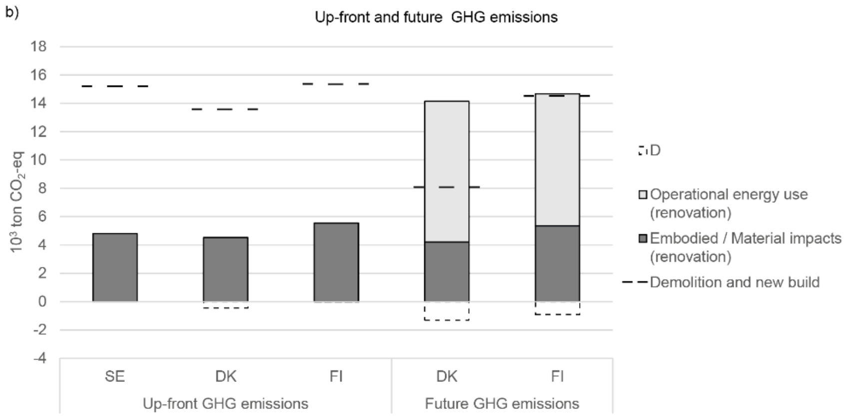


Figure 4-4 Upfront and future impacts from renovation versus new construction using different approaches. From Publication II (Zimmermann, Barjot, et al., 2023)

A different publication also considers the system boundaries. Publication III presents and characterizes different allocation approaches and modeling in LCA of renovation found through a scientific literature review. This concerns the allocation of the existing materials between the consecutive life cycles: Life cycle 1: The existing building before renovation, and life cycle 2: the renovated building (see figure 2-1 in Chapter 2).

One of the methods is the *burden-free approach,* which is illustrated in figure 4-5. The burden-free approach follows the current standardization from CEN/TC 350, where production of existing materials is allocated to the first life cycle. For this approach, the impact on the renovation project is typically limited since production processes generally have the largest emissions. Figure 4-5 illustrates that different system boundaries are used within the burden-free approach: The use stage and EoL stages for existing materials are only sometimes included in renovation studies. Publication III also illustrates that there is a significant workload associated with mapping the materials from the existing building. Approaches that allocate part of the production of existing materials to the renovation projects are also used in literature and are further described in Publication III. These methods, however, do not align with the CEN/TC 350 standardization, which uses the cut-off approach. They would therefore be a challenge to implement in practice due to deviation from the current EPD data used in assessments.

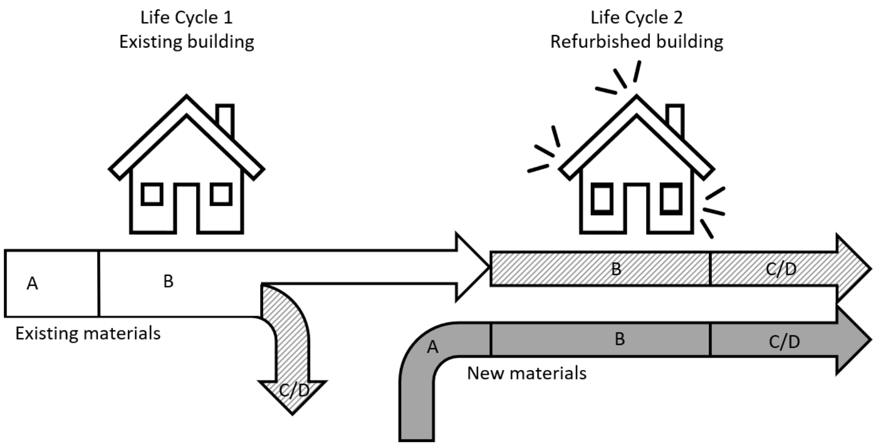


Figure 4-5 Variations in system boundaries for renovation projects (in figure called "refurbishment") using a burden-free approach. The stages in dark grey are typically included, while the hatched stages are only sometimes included. From Publication III (Zimmermann et al., 2022)

Going back again to Publication II, where we considered the national approaches, the knowledge from Publication III becomes relevant. All approaches follow a burden-free approach, but the Danish and Finnish approaches include the hatched stages from figure 4-5. The results illustrated a temporal difference in emissions from existing materials depending on if they are demolished "upfront" (when materials are removed as part of the renovation, or the entire building is demolished) or kept in the building and demolished as part of future emissions. The results for the case building showed that the emissions from existing materials were most significant for the biobased materials. This is because only EoL is considered for the existing materials, and thus the assessment only considered the release (and not the uptake) of the CO_2-storage, when using data following the EN 15804:2012+A1. This can promote reuse, but also burden projects with a high content of biobased material. In the updated version of the standard EN 15804:2012+A2:2019 it will be more transparent what is related to biogenic CO_2, as this is declared separately. The other emissions from existing materials were negligible. The inclusion of existing materials in the assessment should be considered against the practical challenges of accounting for all existing materials.

4.2. INTEGRATION IN THE DESIGN PROCESS

This section considers how we can integrate methodological demands from LCA into the design process. Publication IV investigates this aspect specifically for LCA of renovation, while Publication V also considers the integration of new construction in the design process.

4.2.1. TOOL FOR LCA OF RENOVATION

Section 4.1.4 showed that there can be practical challenges in relation to estimating the material quantities in renovation. Especially the quantities of existing materials in the building contribute to the workload when they are included. Publication IV, therefore, addresses how to quickly estimate the building inventory for renovation projects considering both existing and new materials. The approach has been implemented in the Danish tool for LCA of buildings, LCAbyg.

A parametric model was created, including libraries for existing building components and a library for renovation components, see figure 4-6. The model and libraries are based on an existing multifamily residential building typology. This typology is common in urban housing in Denmark that was originally constructed between 1850 and 1920 (see section drawing of the typology in figure 3-1 in section 3.5). The model is a pilot case, which can only be used for this specific building typology. However, in the future, it can be expanded to include other building typologies. The libraries are implemented in LCAbyg, where material quantities are matched to the LCIA data from Ökobaudat. The operational energy use is not a part of the model. For more information on how the model was created, see the method section in Publication IV.

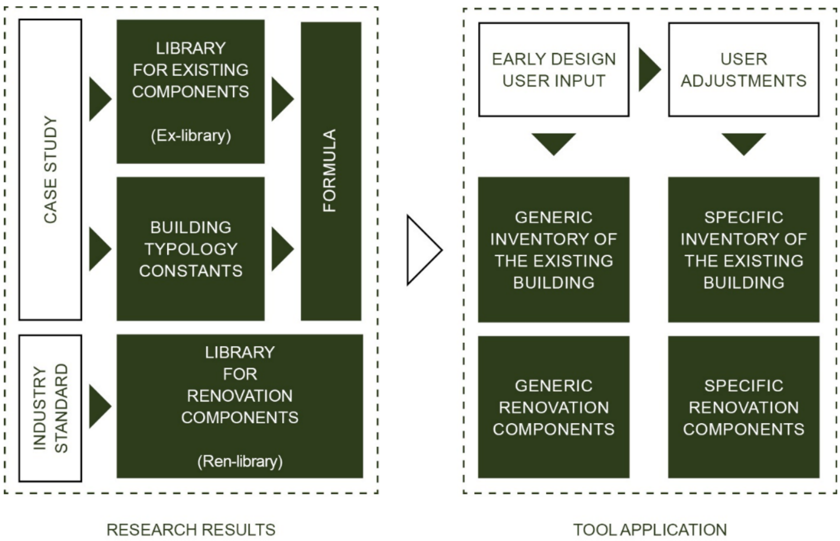


Figure 4-6 Data and use of tool to create the inventory for renovation projects. From publication IV (K. Kanafani et al., 2022)

The tool works by initially prompting the user for eight standardized inputs about the building. The inputs include the building footprint, number of floors, roof type, etc. (see full list in Table 1 in Publication IV), which is typically already available in the early design stages. The tool will then determine the remaining dimensions of the buildings and match these to building components from the library, thus creating the inventory for the existing building. When the inventory for the existing building is created, it is possible to add renovation actions, use the library for new components, and remove some of the existing materials. The approach can work for different design stages, as the user can simply adjust the pre-made building inventory to fit with specific dimensions when these become available, see figure 4-6, on the right side.

The tool makes it easier to perform LCA of existing buildings when no BIM is available. It is possible to use already from early design stages andit can also be used on a larger scale for building stock/material bank screenings. The uncertainty of the model will be high when only the standard inputs are used. This will typically apply to the early design phases, where large uncertainty is also typically accepted (Hollberg et al., 2022). However, with adjustments to fit the specific dimensions, this can be improved.

4.2.2. CURRENT PRACTICE AND NEEDS IN BIM-LCA

While section 4.2.1 considered an approach without the use of digital building models, this section will consider the scenarios where these models are available. Publication V investigates current practices, challenges, and needs from the integration of 3D building models or BIM with tools for performing LCA. The publication has no particular focus on renovation or the existing building.

Qualitative interviews were conducted with informants from the building industry in Denmark on the topic of their current integration process and their challenges and needs for BIM-LCA workflow. Results showed that most companies use a "quantity take-off" approach for the BIM-LCA process, where the data is transferred from the BIM software to – in most cases – an excel sheet, and then manually entered into the LCA-tool. The LCA-tool used was typically LCAbyg, which is a Danish industry tool. There are a few variations in how the data was transferred to Excel, which can be seen in detail in Publication V, figure 6. The extracted data from the BIM is supplemented with data from other sources because the data from the model is not sufficient to create the building inventory, see figure 4-7.

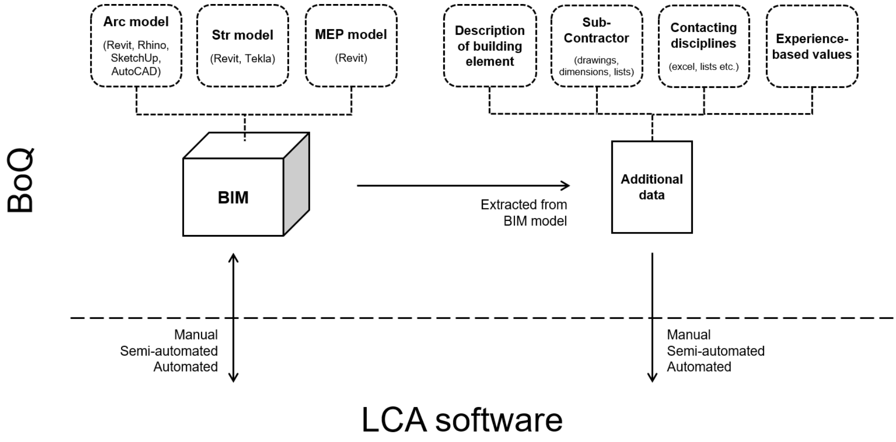


Figure 4-7 Data from BIM and supplementary sources used to perform LCA.. From Publication V (Zimmermann, Bruhn, et al., 2021)

Different challenges for the process were stated by the informants. These challenges were coded into different themes, shown in table 4-2. A more detailed table can be found in Publication V, Table 3. A key area was the data availability and quality in the models. The informants know that the models are not optimal in relation to the quantity take-off needed for an LCA. The reason for this is modeling errors, variations in modelling structure, and a general lack of management of the models in the collaborative process. It was also mentioned that the manual workflow in the current BIM-LCA processes is a cause of human errors and is very time consuming.

Table 4-2 Key areas of challenges identified in Publication V

Challenges	• Lack of building model management for a collaborative process • Workflow errors • Lack of data availability and quality in models • Modeling errors • Variations in the structure of models • Data exchange and matching model data with LCIA data • Manual workflow and large models

For the integration process, the informants mentioned the need for a quick/automated process to make the LCA. This was valuable in general, but especially for the early design stages. Transparency of results was also considered central in an automated process: Errors from the models can more easily be found and fixed if there is transparency in the integration process. Other properties that were mentioned were the possibility to easily evaluate different design solutions, having a visual interface (such as a 3D visualization of the model), and flexible workflow in terms of the data sources used. Similar results were found in a recent study by Hollberg et. al. (2022) for early design. The study also highlighted the fast calculation and transparency as central concerns to make LCAs. See all the properties for the integration process mentioned by the informants in table 4 in Publication V.

From the above, the practice of integrating the digital building models with LCA-tools, shows challenges and workload associated with the quality and completeness of models, which can be considered in future development. Further, the users seek quick and automated processes, but with transparency in the integration process.

4.1. SUMMARY OF FINDINGS

Publication I, II, and III contain analyses of methods and benchmarks for renovation:

Publication I assesses the life cycle GHGe of 23 real-life renovation cases within a Danish context. Results illustrate large potential savings in operational energy use and show that GHGe from the operational energy use were higher than embodied emissions. However, operational emissions are highly influenced by context and scenario modeling for e.g. decarbonization of the energy system.

The embodied emissions were also mapped to see which added functions they relate to. For the embodied emissions, results show that, on average, energy reduction actions contributed to 46% of emissions, whereas the remaining 54% of embodied emissions relate to other functions in the renovation, such as layout, indoor climate, and spatial changes. This highlights the need to consider a wide range of renovation actions, not just those related to reducing operational energy use.

Lastly, the results from Publication I were used to address possible benchmarking of renovation projects. The potential impacts from renovation projects relate to different added functions, making the renovation projects unique and varied. This contributes to the challenges in benchmarking on a building level. Instead, benchmarks for elements or components can be a more viable option.

Publication II analyses the performance of a renovation project against demolition and new construction using three different national approaches. Results illustrate the significance of system boundaries, which varied in the three approaches. Results illustrate a sensitivity to the inclusion of operational energy use due to its large influence on the result. However, the publication also shows that the influence of operational impacts can potentially negate the significance of upfront emissions if they are not emphasized. The upfront emissions are important to stay within our carbon budget in order to limit temperature rise.

The inclusion of existing materials shows to have limited influence in the study. The contribution was mainly due to the release of biogenic carbon from existing materials based on the use of data following the EN 15804:2012+A1. The inclusion of existing materials in the assessment should, therefore be considered against the practical challenges of accounting for all existing materials.

Publication III presents and characterizes different allocation approaches and modeling in LCA of renovation. Different methods are used in literature to allocate impacts between the new LCA of renovation, and the existing building before renovation. One method is a burden-free approach, where only future emissions are considered. However, there is still a variation within this approach of how much of the existing material is considered, if any. The publication also shows that there is a significant workload associated with mapping the materials from the existing building, which should be considered in the development of approaches for the industry.

Publication IV and V contain analyses of the integration in design process:

Publication IV creates a generic library and parametric geometry model based on a building typology study. This tool can be used to automate the life cycle inventory of existing materials in buildings. It helps automate the process of performing LCA for the early design stages and for projects where there is no detailed geometric model or BIM. It can also be used on a larger scale for building stock/material bank screenings.

Publication V investigates current implementation strategies and challenges in BIM-LCA based on interviews with consultants in the Danish building sector. The research shows that they mainly use a “quantity take-off” approach, which involves many manual processes, and how they needed to supplement the data from the models. The building models lack both completeness in data and quality of data. Therefore, the industry needs a more automated integration process to avoid human errors but with transparency in order to easily find and fix errors from e.g. the model. The quick/automated process will be especially valuable in the early design stages. Development is also needed to easily evaluate different design solutions.

CHAPTER 5. DISCUSSION

For this discussion section, the findings are put into perspective by elaborating on three important themes for the future development of LCA of renovation and integration in the digital design process. The chapter has a summary of the themes at the end.

5.1. THE TEMPORAL PERSPECTIVE OF EMISSIONS IN RENOVATION

The service life of a building is long compared to other common products or service applications of LCA. For all publications in this dissertation, a 50-year reference study period (RSP) was used following the Danish approach and representing the service life of the building. This can be considered low compared to the actual technical service life of a building, but a short RSP reduces the time-related uncertainties and is common in existing LCA approaches (Decorte et al., 2022). However, even a “short” RSP of 50 years can seem excessive with the urgent need to reduce GHGe to stay within the carbon budget. Furthermore, the decarbonization of the energy grid, and plans for a zero-carbon future by 2050 push us to prioritize upfront emissions (Röck, Ruschi Mendes Saade, et al., 2019).

The dissertation showed how operational energy use had a significant influence on the emissions from renovation cases. Furthermore, operational energy emissions is often a major deciding factor when comparing different scenarios for the building, such as “demolition and new construction”, “doing nothing” to the building, or making energy retrofits.

“Doing nothing” has the lowest upfront emissions but can have large emissions from operational energy use. Demolition and new construction have a large upfront spike due to the construction of new buildings. However, the operational energy emissions have potential to perform better than in the other scenarios. Renovation projects are characterized by an upfront spike in emissions from the renovation work. In the use stage, the operational energy use has typically been lowered compared to existing conditions. In this comparison, a scenario with low upfront emissions from “doing nothing” is always best in a short time horizon, while having a low operational energy use will perform best over a long time horizon. This was shown in the results in Publication I and in the literature review by Vilches et al. (2017), where energy retrofitting typically resulted in an effective reduction of GHGe over the life cycle. While a long RSP can encourage consideration of future emissions, it can also negate the upfront spike from renovation projects (and the spike from new construction, in comparative studies). Furthermore, the upfront emissions also reflect the emissions that are more certain in the assessment, compared to future emissions that are based on scenario modeling.

It is therefore important in the future development of LCA method and practice how to incentivize the upfront spike, as well as consider the possible trade-offs in relation to the use stage emissions. To fully consider the upfront spikes, methods should consider all upfront life cycle stages, also the construction stage impacts (A4 and A5), and separate declarations for upfront and future emissions.

The uncertainty of future emissions is also higher than upfront emissions. It is, therefore, recommended to consider the modeling and uncertainty of future emissions in assessments of renovation (Amini Toosi et al., 2020; Farsäter et al., 2021). This can be especially important for the energy consumption, which has a significant influence on the result of renovation projects. While the current approaches in e.g. Denmark and Finland already consider changes in the future energy grid, the assessment could still include uncertainty analysis. There exist different scenarios that can be applied for future societal development affecting the results, including the development towards a carbon-neutral future (Bruhn et al., 2023).

The thermal energy supply in buildings can also undergo changes, which has a significant influence on emissions (Galimshina et al., 2021). Publication I also showed the significance of the thermal energy technology: While most of the case buildings are supplied by an average district heating mix, a few cases were supplied by natural gas, which resulted in significantly larger emissions from heating.

Furthermore, there are several documented uncertainties related to operational emissions that are less addressed in literature (Amini Toosi et al., 2020). They include the expected differences in calculated energy demand and actual energy demand, such as the rebound effects, where energy efficiency is often translated into higher consumption (Hansen et al., 2018). Global warming can also affect the heating and cooling demand for the building in the future.

5.2. REGULATORY CONTEXT OF LCA OF RENOVATION

In the revised energy performance of buildings directive (EPBD), it is suggested to include whole-life-carbon from both new construction and renovation projects (European Commission, 2021). Despite previous attention on solely operational emissions, the EPBD now opens for a broader focus to also consider embodied emissions over the building life cycle. This happens alongside a push for deep renovation, where the "renovation wave" of Europe aims to double the annual renovation rate by 2030, resulting in 35 million buildings being renovated by this time (European Commission, 2020).

It is important to reduce embodied emissions from renovation projects due to the magnitude of expected renovation projects, as well as the temporal concerns of upfront carbon spikes from renovation, as discussed in section 5.1. A recent study has also shown that the increase in renovation, without considering the carbon content of materials, will not bring us closer to staying within our climate budget (Priore et al., 2022). Thus, the consideration of embodied emissions in the EPBD is significant for future reduction in renovation. For the consideration of embodied emissions, Publication I showed the importance of considering other emissions than those related to energy reduction, such as layout, because they have a significant influence on results. It is therefore important to avoid or reduce emissions across all new functions in renovation by considering e.g. material choices to stay within the climate budget.

A key to reducing impact when implementing the EPBD is to use benchmarks. Benchmarks can be used to reduce the emissions from buildings and renovation projects by setting a limit value that buildings should comply with. While the EPBD do not mention benchmarking, this is something that can be considered on a national level and with the national approach, similar to new construction.

However, the work in this PhD showed that benchmarking will be difficult for renovation projects due to the variation in the functional qualities of the renovation. But Publication I also suggests benchmarks on a “lower level”, such as for building elements or components. By considering renovation actions on a lower level, the function can be comprised of only new materials, thus being similar to benchmarking components for new construction. Hollberg et al. (2019) suggest to combine bottom-up benchmarks for building elements with top-down benchmarks based on global targets. This approach could be used for renovation projects as well. This benchmark approach provides both incentives to improve the design of the entire building project (from the top-down approach) and gives guidance on how to improve the individual building elements from the bottom-up benchmarks (ibid.). Results from Publication IV showed that a large part of emissions are from completely new building elements, where the bottom-up approach can be implemented similar to new construction. For the top-down approaches, it will be difficult to allocate a generic amount of the carbon budget to a renovation project due to the differences in functionalities as mentioned above. Instead, approaches that allocate emissions based on the added functionalities of the building could be developed: e.g., daylight, elevators, indoor climate, etc. This can also be based on building typologies, the expected use of buildings in geographical areas etc. Nevertheless, a bottom-up approach could be a way to get started on benchmarking renovation while developing a solid approach to top-down benchmarking.

Table 5-1 Examples of how benchmarks could be created for building elements (bottom-up) and potentially implement top-down approaches.

Function	Bottom-up	Top down
Layout	• Benchmarks for flooring and ceiling components • Benchmarks for internal wall elements	• Budget for adapting to different use of the building (e.g. based on regional needs for different building types) • Budget for modernization needs (e.g. based on building typology)

5.3. ADVANCEMENTS IN TOOLS FOR PRACTICAL IMPLEMENTATION

Today, the solutions to ease the practical implementation of LCA is in rapid development. The introduction of LCA on buildings in national legislation has also been a significant driver in the development. The solutions focus on determining the material quantities and integrate with LCA tools. For the Danish context, new tools have been developed to support the process, focusing on solving several of the challenges presented in this dissertation. For instance, the dissertation showed that several data-sources were used to supplement the data from the BIM (see figure 4-7 in section 4.2.2). This has been addressed in a tool aimed towards collecting data from different sources and project partners (Molio, 2023). Thus, aiming the responsibility of data towards the project partners who have the best information on the data. Tools such as this can also help address errors from the models, which was pointed out as a key issue for BIM-LCA in this dissertation.

For the common Danish industry tool, LCAbyg, an API (Application Programming Onterface) has also been made public. This allows for the industry to create their own integration towards e.g., building models or collection of data such as described above, with instant feedback on results. It also supports building design using parametric LCA, by using e.g. Grasshopper to transfer data between the building model and LCA-tool (Säwén et al., 2022). The parametric approach allows for generating quick design alternatives and using optimization techniques. For early design stages, the component catalogue in LCAbyg can be used.

A specific research focus can be aimed towards the early design stages, as this is where information on LCA is most likely to influence the design. Developing tools for this stage has its own set of traits (Hollberg et al., 2022), for instance, allowing results to be less precise. For the early stages, Llatas et al. (2022) suggest exploring the options of an “enriched BIM” approach in the early design. For this approach, environmental data is added to BIM-objects, as specified in the standard ISO/CD 22057 (ISO, 2022). For early implementation *without* any 3D model, a new library approach has been developed for the Danish context (*LCAlive*, n.d.). The approach is similar to the one presented in this dissertation, where the geometry is estimated based on simple user input and matched to a component library. However, while the approach in this dissertation is aimed toward renovation of a specific multifamily building typology, this tool is aimed towards new construction of single-family houses. Approaches, where no 3D model is used, are important for the instances where no model is available.

While component libraries and formulas or 3D models can help aid the LCA of renovation, it will significantly ease the implementation when existing materials are not included in the assessment. This is due to the workload and challenges in estimating and modeling the existing materials (Volk et al., 2014).

5.4. SUMMARY OF DISCUSSION

The discussion presents three core subjects related to the method and benchmark for renovation and implementation in the building sector.

First, the temporal perspective is of paramount importance for LCA on renovation projects and for the comparison of different scenarios. This is due to the trade-off between upfront embodied emissions and future operational savings, resulting in different performances depending on the RSP considered. A long time horizon can negate the upfront spike in emissions, which can compromise our ability to reach carbon budgets and thus withstand the current climate crisis. Several parameters can also affect future emissions, influencing results and conclusions, for instance, the decarbonization of the energy grid. These uncertainties should be considered in future development.

Second, the current regulatory context has a focus on reducing the operational energy use of existing buildings. This is visible through EU initiatives such as the "renovation wave” and the new energy performance of buildings directive (EBPD). The goal is to double the annual renovation wave by 2030, resulting in 35 million buildings being renovated by this time. With the current regulatory focus on increasing renovations, it is important to simultaneously reduce the embodied emissions from the materials used in the renovation. This can be done by benchmarking emissions; however, the dissertation has shown that the functional qualities (and thus emissions) of renovation projects differ significantly. Therefore, benchmark approaches for renovation projects should consider using a combination of bottom-up and top-down benchmarks. This benchmark approach provides incentives to improve the design of the entire building project and gives guidance on how to improve the individual building elements.

Lastly, the implementation of LCA in the industry practice is vital for the lowering of emissions. The demands in terms of national and simplified LCA approaches should be “answered” by the tools and developments in integration processes and at the same time, they need to answer the demands of the users: Their collaborative process and their different uses of 3D models. This process is ongoing and targets different users and different challenges.

CHAPTER 6. CONCLUSIONS

The dissertation has identified and evaluated, for future method development and policymaking, significant methodological variations and challenges in relation to performing and benchmarking LCA of renovation, and suggested how methods and benchmarks can be implemented in practice. Furthermore, the dissertation has identified needs for future development of digital tools to integrate LCA in the design process and develop practical approaches.

The five sub-questions and the main research question are answered below. The main research question synthesizes the findings from the five sub-questions.

6.1. RESEARCH QUESTIONS ANSWERED

SQ1: ***What are GHG emissions from real-life renovation cases?***

To answer this, life cycles assessment was performed for 23 real-life renovation cases in a Danish context to show the environmental profile of different renovation projects based on their contribution to embodied and operational GHGe. The results showed higher contributions from operational emissions than embodied with average values of 6.0 kg CO_2-eq/m^2/year and 2.8 kg CO_2-eq/m^2/year, respectively, over 50 years. The operational savings from the renovation were between 20%-65%. Especially the operational emissions should be seen in the light of the context and modeling, where energy mixes, climate, and scenario modeling have a large influence on results. The GHGe varied a lot between cases for both operational and embodied emissions due to the different functions provided. Energy reduction, on average, are related to 46% of the embodied emissions. While the remaining 54% of embodied emissions are related to other functions, such as layout, indoor climate, and spatial changes. The results clearly indicate operational savings potential from renovation, which is supported by existing literature. However, it also shows the significance of embodied emissions in renovation, which are not focused on energy reduction. While political focus is on reducing energy demand, it is important that these potential impacts are considered in future renovation design and policy-making.

SQ2: ***What are design incentives from different methodological approaches?***

A typical renovation project was compared to demolition and new construction, using three different national LCA approaches. Results illustrated the significance of system boundaries in the assessment. For instance, results illustrated a sensitivity to the inclusion of operational energy use due to its large influence on the result. However, the significance of operational energy use can limit incentives to reduce upfront emissions. Reducing upfront emissions is important to stay within our carbon budget. Therefore, it is important to consider all upfront emissions (A1-A5 in EN 15978) in the assessment of renovation projects. Further, it should be considered to declare emissions separately for upfront and future emissions and improve modeling and uncertainty analysis for operational energy use.

The inclusion of existing materials showed to have limited influence on incentives in the study, however, future studies should consider how to further incentivize reuse of the existing materials within or outside the renovation project. For the practical assessments in the building sector, the inclusion of existing materials should be considered against the practical challenges of accounting for all existing materials.

SQ3: ***What method-related aspects should be considered when benchmarking renovation?***

The assessment of 23 real-life renovation cases showed that life cycle GHGe varies significantly for renovation projects, even though most of them are considered “major renovation”, according to the definition in the EPBD. The emissions from renovation projects contributed to a variety of different functions that improve the existing building and it is important to find an effective but practical solution to limit these emissions to stay within the carbon budget. The differences in added functionality, along with the different conditions of the existing building, complicate the benchmarking of renovation projects on a building level. A possibility is, therefore, to look at benchmarks on a “smaller” level, such as the building elements and components. Bottom-up element benchmarks can be combined with top-down benchmarks based on carbon budgets and value-based allocation.

SQ4: ***How can LCA of renovation be implemented in practice?***

The research showed that the inclusion of existing materials can add a significant workload to the performance of LCA on renovation projects. To ease the workload, a generic library and parametric geometry model were created based on a building typology study. This approach can be used to automate the life cycle inventory of existing materials in buildings. The approach helps automate the process of performing LCA for the early design stages and for projects where there is no detailed geometric model or BIM.

SQ5: ***What are the current approaches and challenges within the integration of the building model and LCA tools?***

Qualitative interviews were conducted with the industry for projects where geometric models or BIM exist, including for new construction. Results showed that BIM-LCA approaches involve many manual processes that are both time-consuming and cause human errors. Furthermore, the building models lack both completeness in data and quality of data. Therefore, the industry needs a more automated integration process to avoid human errors but with transparency in order to easily find and fix errors from e.g. the model. The quick/automated process will be especially valuable in the early design stages. Development is also needed to easily evaluate different design solutions.

RQ: ***How can LCA for the building industry be developed within the topics of renovation and digital tools for the design process to reduce GHG emissions of buildings?***

Significant savings in operational GHGe of 20%-65% is possible from renovation projects in a Danish context. Significant operational energy savings can become a reality in the millions of buildings that are targeted throughout Europe in the "renovation wave" that aims to double the annual renovation rate by 2030. However, it is important to consider the upfront spike in embodied emissions from materials, which may jeopardize our opportunity to stay within the carbon budget that is set to limit the global temperature rise to 1.5 degrees. Furthermore, the decarbonization of the energy grid and plans for a zero-carbon future by 2050 push us to prioritize upfront emissions from materials. The research has unveiled method considerations within the assessment of renovation projects in the industry that should be considered in the continued development. Results showed that the inclusion of operational energy use has a significant influence on GHGe in renovation projects. This can negate the incentive to reduce upfront emissions, and therefore, future development needs to consider a temporal perspective by e.g. dividing the assessment of GHGe into upfront and future emissions and improve the modeling and uncertainty of future emissions from operational energy use.

It is also important to consider the whole renovation project, as embodied emissions stem from a variety of functions beyond energy reduction. The unique nature of renovation projects is a challenge for benchmarking, which is why the most easily implemented solution for practice is to consider bottom-up benchmarks for building elements. These can also be combined with a top-down benchmark approach based on the remaining carbon budget.

For integration in the design process, solutions can be developed that can reduce the workload in renovation projects and are easy to implement in early design stages. The use of BIM or 3D models in LCA is in rapid development, but it is still important to consider the automatization but also transparency of the integration process due to the limitations of the models in the industry.

6.2. FUTURE RESEARCH

Further research within the field of benchmarks should develop bottom-up benchmarks for building elements to improve the performance of building elements in renovation. Further, research should investigate top-down benchmarks based on functional requirements in the building to stay within the carbon budget.

Further research within the field of uncertainty analysis should consider different scenarios of future emissions in renovation, especially emissions from energy consumption. This can include decarbonization of the energy grid, rebound effects, future heating demands, etc.

Further research within the field of low-carbon strategies should investigate potential savings from material choices in the renovation, including materials that contribute to e.g. layout and indoor climate.

Further research within the field of BIM-LCA should develop an automated integration process that allows for transparency and supports quick evaluation of different design solutions.

LITERATURE LIST

Amini Toosi, H., Lavagna, M., Leonforte, F., Del Pero, C., & Aste, N. (2020). Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review. *Sustainable Cities and Society*, *60*(May), 102248. https://doi.org/10.1016/j.scs.2020.102248

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. In *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2016.09.058

Antón, L. Á., & Díaz, J. (2014). Integration of life cycle assessment in a BIM environment. *Procedia Engineering*, *85*, 26–32. https://doi.org/10.1016/j.proeng.2014.10.525

Balouktsi, M., Lützkendorf, T., Röck, M., Passer, A., Reisinger, T., & Frischknecht, R. (2020). Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72. *IOP Conference Series: Earth and Environmental Science*, *588*(3). https://doi.org/10.1088/1755-1315/588/3/032023

Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, *60*, 81–92. https://doi.org/10.1016/J.BUILDENV.2012.11.009

Beemsterboer, S., Baumann, H., & Wallbaum, H. (2020). Ways to get work done: a review and systematisation of simplification practices in the LCA literature. *The International Journal of Life Cycle Assessment*, *25*(11), 2154–2168. https://doi.org/10.1007/s11367-020-01821-w

Bionova Ltd. (n.d.). *One Click LCA*. www.oneclicklca.com

Boverket. (2022). *Climate database*. https://www.boverket.se/en/start/building-in-sweden/developer/rfq-documentation/climate-declaration/climate-database/about-climate-database/

Brinkmann, S. S. (2013). Qualitative interviewing. In *Qualitative interviewing*. Oxford University Press.

Bruhn, S., Sacchi, R., Cimpan, C., & Birkved, M. (2023). Ten questions concerning prospective LCA for decision support for the built environment. *Building and*

Environment, *242*, 110535. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110535

Cavalliere, C., Habert, G., Dell'Osso, G. R., & Hollberg, A. (2019). Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *Journal of Cleaner Production*, *211*, 941–952. https://doi.org/10.1016/j.jclepro.2018.11.247

CEN. (2012a). *EN 15804+A1 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*. https://webshop.ds.dk/en/standard/M254454/ds-en-15804-2012

CEN. (2012b). *EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

CEN. (2019). *EN 15804:2012+a2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*. https://www.en-standard.eu/bs-en-15804-2012-a2-2019-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/

CEN. (2021a). *DRAFT: prEN 15978-1 Sustainability of construction works - Methodology for the assessment of performance of buildings - Part 1: Environmental Performance*.

CEN. (2021b). *DRAFT: prEN 17680 Sustainability of construction works - Evaluation of the potential for sustainable refurbishment of buildings*.

Copernicus. (2023, August). *July 2023 sees multiple global temperature records broken*. https://climate.copernicus.eu/july-2023-sees-multiple-global-temperature-records-broken

COWI. (2020). *Opdaterede emissionsfaktorer for el og fjernvarme*. https://bpst.dk/da/Byggeri/Lister/Publikationsliste?theme=Indeklima

CSTB. (n.d.). *EveBIM*. Retrieved April 23, 2021, from https://www.evebim.fr/

Danish Energy Agency. (2021). *Klimastatus og -fremskrivning 2021*. https://ens.dk/service/fremskrivninger-analyser-modeller/klimastatus-og-fremskrivning-2023

Danish housing and planning authority. (2023). *Danish Building Regulations*.

https://bygningsreglementet.dk/

De Wolf, C., Pomponi, F., & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, *140*, 68–80. https://doi.org/10.1016/j.enbuild.2017.01.075

Decorte, Y., Bossche, N. Van Den, & Steeman, M. (2022). Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction. *The International Journal of Life Cycle Assessment*. https://doi.org/10.1007/s11367-022-02114-0

Di Bari, R., Horn, R., Bruhn, S., Alaux, N., Ruschi Mendes Saade, M., Soust-Verdaguer, B., Potrč Obrecht, T., Hollberg, A., Birgisdottír, H., Passer, A., & Frischknecht, R. (2022). Buildings LCA and digitalization: Designers' toolbox based on a survey. *IOP Conference Series: Earth and Environmental Science*, *1078*(1). https://doi.org/10.1088/1755-1315/1078/1/012092

Díaz, J., & Antön, L. Á. (2014). Sustainable construction approach through integration of LCA and BIM tools. *Computing in Civil and Building Engineering - Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering*, *June 2014*, 283–290. https://doi.org/10.1061/9780784413616.036

Dodd, N., Donatello, S., & Cordella, M. (2021). Level(s) – A common EU framework of core sustainability indicators for office and residential buildings. *Available Online: Https://Susproc.Jrc.Ec.Europa.Eu/Efficient_Buildings/Documents.Html*, *January*, 1–68.

Edmondson, A. C., & Mcmanus, S. E. (2007). Methodological fit in management field research. *The Academy of Management Review*, *32*(4), 1155–1179. https://doi.org/10.2307/20159361

Engelmark, J. (1983). *Copenhagen flatted housing 1850-1900*. SBI forlag. https://sbi.dk/Pages/Koebenhavnsk-etageboligbyggeri-1850-1900.aspx

Erlandsson, M., & Borg, M. (2003). Generic LCA-methodology applicable for buildings, constructions and operation services—today practice and development needs. *Building and Environment*, *38*(7), 919–938. https://doi.org/https://doi.org/10.1016/S0360-1323(03)00031-3

European Green Deal, (2019). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents

European Commission. (2020). Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. *Official Journal of the European Union*, 26. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

European Commission. (2021). Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast). *Official Journal of the European Union*, *0426*, 10–27. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

European Parliament. (2023). *EU measures against climate change*. https://www.europarl.europa.eu/news/en/headlines/society/20180703STO07129/eu-measures-against-climate-change?&at_campaign=20234-Green&at_medium=Google_Ads&at_platform=Search&at_creation=RSA&at_goal=TR_G&at_audience=consequences of climate change&at_topic=

Farsäter, K., Wahlström, Å., & Johansson, D. (2021). Uncertainty analysis of climate change potential assessments of five building energy renovation measures in Sweden. *SN Applied Sciences*, *3*(12). https://doi.org/10.1007/s42452-021-04838-4

Federal Institute for Research on Building. (2014). *eLCA*. Urban Affairs and Spatial Development. https://www.bauteileditor.de/

Figl, H., Ilg, M., & Battisti, K. (2019). 6D BIM-Terminal: Missing Link for the design of CO-neutral buildings. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012104

Finnish Environment Institute. (2023). *Emissions database for construction*. www.CO2data.fi

Flyvbjerg, B. (2011). Five Misunderstandings About Case-Study Research. *Qualitative Research Practice*, 390–404. https://doi.org/10.4135/9781848608191.d33

Fonseca Arenas, N., & Shafique, M. (2023). Recent progress on BIM-based sustainable buildings: State of the art review. *Developments in the Built Environment*, *15*. https://doi.org/10.1016/j.dibe.2023.100176

Frischknecht, R. (2010). LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency. *The International Journal of Life Cycle Assessment*, *15*(7), 666–671. https://doi.org/10.1007/s11367-010-0201-6

Galimshina, A., Moustapha, M., Hollberg, A., Padey, P., Lasvaux, S., Sudret, B., & Habert, G. (2021). What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one. *Energy and Buildings*, *251*, 111329. https://doi.org/https://doi.org/10.1016/j.enbuild.2021.111329

Geng, S., Wang, Y., Zuo, J., Zhou, Z., Du, H., & Mao, G. (2017). Building life cycle assessment research: A review by bibliometric analysis. *Renewable and Sustainable Energy Reviews*, *76*, 176–184. https://doi.org/https://doi.org/10.1016/j.rser.2017.03.068

Ghose, A., McLaren, S. J., Dowdell, D., & Phipps, R. (2017). Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. *Building and Environment*, *117*, 274–287. https://doi.org/10.1016/j.buildenv.2017.03.012

Goldstein, B., & Rasmussen, F. N. (2018). LCA of Buildings and the Built Environment. In M. Z. Hauschild, R. K. Rosenbaum, & S. I. Olsen (Eds.), *Life Cycle Assessment - Theory and Practice* (1st ed. 20). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Hansen, A. R., Gram-Hanssen, K., & Knudsen, H. N. (2018). How building design and technologies influence heat-related habits. *Building Research & Information*, *46*(1), 83–98. https://doi.org/10.1080/09613218.2017.1335477

Haugbølle, K., Mahdi, V., Morelli, M., & Wahedi, H. (2021). *BUILD Levetidstabel*. https://build.dk/Pages/BUILD-levetidstabel.aspx

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life Cycle Assessment - Theory and Practice* (1st ed. 20). Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Hollberg, A., Lützkendorf, T., & Habert, G. (2019). Top-down or bottom-up? – How environmental benchmarks can support the design process. *Building and Environment*, *153*, 148–157. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.02.026

Hollberg, A., Tjäder, M., Ingelhag, G., & Wallbaum, H. (2022). A Framework for User Centric LCA Tool Development for Early Planning Stages of Buildings. In *Frontiers in Built Environment* (Vol. 8). https://www.frontiersin.org/articles/10.3389/fbuil.2022.744946

Horn, R., Ebertshäuser, S., Di Bari, R., Jorgji, O., Traunspurger, R., & von Both, P. (2020). The BIM2LCA approach: An industry foundation classes (IFC)-based interface to integrate life cycle assessment in integral planning. *Sustainability*

(Switzerland), *12*(16), 1–30. https://doi.org/10.3390/su12166558

Hussien, A., Abdeen Saleem, A., Mushtaha, E., Jannat, N., Al-Shammaa, A., Bin Ali, S., Assi, S., & Al-Jumeily, D. (2023). A statistical analysis of life cycle assessment for buildings and buildings' refurbishment research. *Ain Shams Engineering Journal*, *14*(10), 102143. https://doi.org/https://doi.org/10.1016/j.asej.2023.102143

Huuhka, S., Moisio, M., Salmio, E., Köliö, A., & Lahdensivu, J. (2023). Renovate or replace? Consequential replacement LCA framework for buildings. *Buildings and Cities*, *4*(1), 212–228. https://doi.org/10.5334/bc.309

IPCC. (2023). *Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Issue 1). https://www.ipcc.ch/report/sixth-assessment-report-cycle/

ISO/TC 59/SC 17. (2002). *Sustainability in buildings and civil engineering works*. https://www.iso.org/committee/322621.html

ISO. (2006a). *ISO 14040: Environmental management – Life cycle assessment – Principles and framework.*

ISO. (2006b). *ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.*

ISO. (2021). *ISO 21678:2020 Sustainability in buildings and civil engineering works – Indicators and benchmarks – Principles, requirements and guidelines*. https://www.iso.org/standard/71344.html

ISO. (2022). *ISO/CD 22057 Sustainability in buildings and civil engineering works – Data templates for the use of environmental product declarations (EPDs) for construction products in building*. https://www.iso.org/standard/72463.html

John, V. (2012). *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings* [ETH]. https://doi.org/10.3929/ETHZ-A-007607252

Kanafani, K., Garnow, A., Zimmermann, R., Sørensen, C., Stapel, E., & Birgisdottir, H. (2022). Automated Life cycle inventories for existing buildings - a parametric reference model approach. *IOP Conference Series: Earth and Environmental Science*, *1078*(1). https://doi.org/10.1088/1755-1315/1078/1/012097

Kanafani, Kai, Zimmermann, R. K., Rasmussen, F. N., & Birgisdóttir, H. (2019). Early Design Stage Building LCA using The LCAbyg Tool: New Strategies For Bridging The Data Gap. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012117

Kanafani, Kai, Zimmermann, R. K., Rasmussen, F. N., & Birgisdóttir, H. (2021). Learnings from developing a context-specific LCA tool for buildings—the case of lcabyg 4. *Sustainability (Switzerland)*, *13*(3), 1–23. https://doi.org/10.3390/su13031508

Kiss, B., Röck, M., Passer, A., & Szalay, Z. (2019). A cross-platform modular framework for building Life Cycle Assessment. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012103

Laakso, M., & Kiviniemi, A. (2012). The IFC standard - A review of history, development, and standardization. *Electronic Journal of Information Technology in Construction*, *17*(May), 134–161.

LCAlive. (n.d.). https://lcalive.dk/

Ligurgo, V., Philippette, T., Fastrez, P., Collard, A. S., & Jacques, J. (2018). A Method Combining Deductive and Inductive Principles to Define Work-Related Digital Media Literacy Competences. *Communications in Computer and Information Science*, *810*(July), 245–254. https://doi.org/10.1007/978-3-319-74334-9_26

LLatas, C., Soust-Verdaguer, B., Hollberg, A., Palumbo, E., & Quiñones, R. (2022). BIM-based LCSA application in early design stages using IFC. *Automation in Construction*, *138*, 104259. https://doi.org/https://doi.org/10.1016/j.autcon.2022.104259

Lützkendorf, T., & Balouktsi, M. (2023). *Benchmarking and target-setting for the life cycle-based environmental performance of buildings* (Issue February). https://annex72.iea-ebc.org/Data/publications/EBC_Annex_72_Benchmarking_for Environmental_Performance_of_Buildings_2023.pdf

Malmqvist, T., Borgström, S., Brismark, J., & Erlandsson, M. (2023). *Referensvärden för klimatpåverkan vid uppförande av byggnader. Version 2, 2023*. https://vbn.aau.dk/en/publications/whole-life-carbon-assessment-of-60-buildings-possibilities-to-dev

Marsh, R. (2016). LCA profiles for building components: strategies for the early design process. *Building Research & Information*, *44*(4), 358–375.

https://doi.org/10.1080/09613218.2016.1102013

Marsh, R., Rasmussen, F. N., & Birgisdóttir, H. (2018). Embodied carbon tools for architects and clients early in the design process. In F. Pomponi, C. De Wolf, & A. Moncaster (Eds.), *Embodied Carbon in Buildings: Measurement, Management, and Mitigation*.

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L., & Verbeeck, G. (2018). Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Building and Environment*, *133*(February), 228–236. https://doi.org/10.1016/j.buildenv.2018.02.016

Ministry of the Environment. (2022). Decree of the Ministry of the Environment on the climate declaration of a building (draft for public consultation). *Indoor Climate and Ventilation of New Buildings*, *September*, 1–16. https://ym.fi/en/the-national-building-code-of-finland

Molio. (2023). *LCAcollect*. https://molio.dk/produkter/digitale-vaerktojer/lcacollect

Nwodo, M. N., & Anumba, C. J. (2019). A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*, *162*, 106290. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106290

Obrecht, Tajda Potrč, Jordan, S., Legat, A., Mendes Saade, M. R., & Passer, A. (2021). An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment. *Journal of Cleaner Production*, *327*(September), 129527. https://doi.org/10.1016/j.jclepro.2021.129527

Obrecht, Tajda Potrč, Jordan, S., Legat, A., & Passer, A. (2021). The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures. *International Journal of Life Cycle Assessment*, *26*(5), 839–851. https://doi.org/10.1007/s11367-021-01920-2

Obrecht, Tajda Potro, Röck, M., Hoxha, E., & Passer, A. (2020). *BIM and LCA Integration : A Systematic Literature Review*.

Ökobaudat. (2023). *Ökobaudat*. https://www.oekobaudat.de/

OneClickLCA. (2022). *Construction Carbon Regulations In Europe*. https://www.oneclicklca.com/construction-carbon-regulations-in-europe/

Paré, G., & Kitsiou, S. (2017). Methods for Literature Reviews. In *Handbook of* *eHealth Evaluation: An Evidence-based Approach*. University of Victoria Libraries.

Pomponi, F., & Moncaster, A. (2018). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*, *81*, 2431–2442. https://doi.org/https://doi.org/10.1016/j.rser.2017.06.049

Priore, Y. D., Jusselme, T., & Habert, G. (2022). Exploring long-term building stock strategies in Switzerland in line with IPCC carbon budgets. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012023. https://doi.org/10.1088/1755-1315/1078/1/012023

Rådet for bæredygtigt byggeri. (2023). *DGNB*. https://rfbb.dk/dgnb-certificering

Rasmussen, F. N., Malmqvist, T., & Birgisdóttir, H. (2020). Drivers, barriers and development needs for LCA in the Nordic building sector - A survey among professionals. *IOP Conference Series: Earth and Environmental Science*, *588*(3). https://doi.org/10.1088/1755-1315/588/3/032022

Rasmussen, Freja Nygaard. (2020). *Low-Carbon Building Design in Danish Method and Practice*. Aalborg Universitetsforlag. https://vbn.aau.dk/en/publications/5648645d-bea1-4292-ade6-14c4e9d2610c

Rasmussen, Freja Nygaard, & Birgisdóttir, H. (2016). *Development of the LCAbyg tool: influence of user requirements and context* (C. ZEBAU – Centre for Energy Architecture and the Environment GmbH (Ed.)). https://doi.org/10.5445/IR/1000051699

Rasmussen, Freja Nygaard, Ganassali, S., Zimmermann, R. K., Lavagna, M., Campioli, A., & Birgisdóttir, H. (2019). LCA benchmarks for residential buildings in Northern Italy and Denmark–learnings from comparing two different contexts. *Building Research and Information*, *47*(7), 833–849. https://doi.org/10.1080/09613218.2019.1613883

Rasmussen, Freja Nygaard, Malmqvist, T., Moncaster, A., Wiberg, A. H., & Birgisdóttir, H. (2018). Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. *Energy and Buildings*, *158*, 1487–1498. https://doi.org/10.1016/j.enbuild.2017.11.013

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment*, *140*, 153–161. https://doi.org/10.1016/J.BUILDENV.2018.05.006

Röck, M., Passer, A., Ramon, D., & Allacker, K. (2019). The coupling of BIM and LCA—challenges identified through case study implementation. In R. Caspeele, L. Taerwe, & D. Frangopol (Eds.), *Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision* (pp. 841–846). Taylor & Francis Group. https://graz.elsevierpure.com/en/publications/the-coupling-of-bim-and-lcachallenges-identified-through-case-stu

Röck, M., Ruschi Mendes Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., Frischknecht, R., Habert, G., & Lützkendorf, T. (2019). Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation. *Applied Energy*, *258*(June), 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Ruuska, A. (2018). *Sustainability of buildings - New perspectives on material-related environmental impacts of buildings*. Aalto University.

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2019). Integration of LCA and LCC analysis within a BIM-based environment. *Automation in Construction*, *103*(September 2018), 127–149. https://doi.org/10.1016/j.autcon.2019.02.011

Säwén, T., Magnusson, E., Sasic Kalagasidis, A., & Hollberg, A. (2022). Tool characterisation framework for parametric building LCA. *IOP Conference Series: Earth and Environmental Science*, *1078*(1), 012090. https://doi.org/10.1088/1755-1315/1078/1/012090

Scholten, N. P. M., & van Ewijk, H. (2013). Environmental Performance Regulations in the Netherlands. *4th International Conference Civil Enginerring, Part I, Building and Renovation*, 245–249.

Shahi, S., Esnaashary Esfahani, M., Bachmann, C., & Haas, C. (2020). A definition framework for building adaptation projects. *Sustainable Cities and Society*, *63*(June), 102345. https://doi.org/10.1016/j.scs.2020.102345

Skillington, K., Crawford, R. H., Warren-Myers, G., & Davidson, K. (2022). A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. *Energy Policy*, *168*, 112920. https://doi.org/https://doi.org/10.1016/j.enpol.2022.112920

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/https://doi.org/10.1016/j.jbusres.2019.07.039

Soust-Verdaguer, B., Llatas, C., & García-Martínez, A. (2017). Critical review of bim-based LCA method to buildings. *Energy and Buildings*, *136*, 110–120.

https://doi.org/10.1016/J.ENBUILD.2016.12.009

Sphera. (2023). *Sphera*. https://sphera.com/product-sustainability-gabi-data-search/

Suri, H. (2011). Purposeful Sampling in Qualitative Research Synthesis. *Qualitative Research Journal*, *11*(2), 63–75. https://doi.org/10.3316/QRJ1102063

Directive 2014/24/EU, Pub. L. No. 2014/24/EU, Official Journal of the European Union 65 (2014). https://doi.org/10.5040/9781509923205.0008

The Swedish Parliament. (2021). *Act (2021:787) on climate declaration for buildings*. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2021787-om-klimatdeklaration-for-byggnader_sfs-2021-787

Theißen, S., Höper, J., Drzymalla, J., Wimmer, R., Markova, S., Meins-Becker, A., & Lambertz, M. (2020). Using Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA. *Sustainability*, *12*(14), 5644. https://doi.org/10.3390/su12145644

Tsikos, M., & Negendahl, K. (2017). Sustainable Design with Respect to LCA Using Parametric Design and BIM Tools. *World Sustainable Built Environment Conference*, *June*, 9. http://orbit.dtu.dk/files/133787517/Sustainable_Design_with_Respect_to_LCA_Using_Parametric_Design_and_BIM_Tools.pdf

UN. (2015). *Paris Agreement*. https://www.un.org/en/climatechange/paris-agreement

UN. (2023a). Hottest July ever signals ‘era of global boiling has arrived’ says UN chief. *UN News*. https://news.un.org/en/story/2023/07/1139162

UN. (2023b). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement

UNEP. (2022). *2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings*, *135*, 286–301. https://doi.org/10.1016/j.enbuild.2016.11.042

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, *38*, 109–127. https://doi.org/10.1016/j.autcon.2013.10.023

Wittstock, B., Saunders, L., Nibel, S., Fullana-i-Palmer, P., Mundy, J.-A., & Sjöström, C. (2012). *EeBGuide Guidance Document Part B: Buildings*. https://www.eebguide.eu/?page_id=704

WMO. (2023). July 2023 is set to be the hottest month on record. *World Meteorological Organization*. https://public.wmo.int/en/media/press-release/july-2023-set-be-hottest-month-record

Yin, R. K. (2018). *Case study research and Applications : design and methods* (6. edition). Sage.

Zimmermann, R.K., Kanafani, K., Nygaard Rasmussen, F., & Birgisdóttir, H. (2019). Early Design Stage Building LCA using the LCAbyg tool: Comparing Cases for Early Stage and Detailed LCA Approaches. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012118

Zimmermann, Regitze Kjær, Andersen, C. M. E., Kanafani, K., & Birgisdottir, H. (2021). *Whole Life Carbon Assessment of 60 buildings Possibilities to develop benchmark values for LCA of buildings*.

Zimmermann, Regitze Kjær, Barjot, Z., Rasmussen, F. N., Malmqvist, T., Kuittinen, M., & Birgisdottir, H. (2023). GHG emissions from building renovation versus new-build : incentives from assessment methods. *Buildings and Cities*, *4*(1), 274–291. https://doi.org/10.5334/bc.325

Zimmermann, Regitze Kjær, Bruhn, S., & Birgisdóttir, H. (2021). BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs. *Sustainability*, *13*(10), 5455. https://doi.org/10.3390/su13105455

Zimmermann, Regitze Kjær, Rasmussen, F. N., & Birgisdóttir, H. (2023). Whole life GHG emissions from 23 building renovation cases – contributions from energy reduction versus other renovation actions. *Energy & Buildings*.

Zimmermann, Regitze Kjær, Rasmussen, F. N., Kanafani, K., Malabi Eberhardt, L. C., & Birgisdóttir, H. (2022). Reviewing allocation approaches and modelling in LCA for building refurbishment. *IOP Conference Series: Earth and Environmental Science*, *1078*(1). https://doi.org/10.1088/1755-1315/1078/1/012095

APPENDICES

Appendix A. Publication I

Publication I: **Whole life GHG emissions from 23 building renovation cases – contributions from energy reduction versus other renovation actions**. Zimmermann, R. K., Rasmussen, F. N., & Birgisdottir, H. Submitted to Energy & Buildings, 2023

Whole life GHG emissions from 23 building renovation cases – contributions from energy reduction versus other renovation actions

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ABSTRACT

Renovation is a circular economy principle to extend the building life and lower the large environmental burden of buildings. While political initiatives focus on energy efficiency to reduce greenhouse gas emissions (GHGe), there is currently a lack of knowledge about GHGe from energy efficiency measures versus measures for other functions in renovation. The aim of this study is therefore to investigate the life-cycle based GHGe from the multitude of changed functions in a larger sample of real-life renovation cases, using the Danish context as an example. The calculations were performed using the Danish national tool for life-cycle assessment on buildings, LCAbyg. Results for the cases showed large differences in emissions from renovation projects. On average, embodied emissions had a value of 2.8 kg CO_2-eq/m^2/year, while operational emissions were 6.0 kg CO_2-eq/m^2/year with a 50-year reference study period. For the embodied emissions, energy reduction actions and local energy production contributed to 46%. The remaining 54% were ascribed to other new functions in the renovation including internal layout, indoor climate, daylight, elevators, balconies, and spatial changes. The elements that contributed the most to embodied GHGe in the renovation projects were the building envelope and building services. The results of this study are significant for future work on benchmarking renovation.

KEYWORDS

renovation; life cycle assessment (LCA); building energy use; building assessment method; refurbishment; benchmarking; circular economy (CE)

1 INTRODUCTION

Buildings contribute to 40% of final energy consumption, in Europe, and account for almost the same share of energy-related greenhouse gas emissions (GHGe) [1]. For that reason, initiatives such as the "renovation wave" of Europe have been developed with the goal of reducing the operational energy use of existing buildings [2]. Furthermore, renovation follows the circular economy principles by extending the life of the building [3]. The renovation wave aims to double the annual renovation rate by 2030, resulting in 35 million buildings renovated at this time. Thus, the revised energy performance of buildings directive (EPBD), includes initiatives to reduce the energy need for existing buildings [1]. The initiative is related to the European "green deal" and the European climate law, which aims to achieve a climate-neutral EU by 2050 [4,5].

However, optimizing energy performance of existing buildings will entail additional embodied emissions, thereby reducing the remaining global carbon budget outlined by the IPCC. These embodied emissions are related to manufacturing, transport, replacements, etc. from the added materials in renovation projects. The revised EPBD suggests to include whole-life-carbon declarations from new constructions and renovations, thus considering both embodied and operational emissions over the building life cycle [1]. Whole-life-carbon is typically addressed through the standardized life cycle assessment (LCA), which is an approach commonly used to assess the environmental impacts of buildings [6].

A growing number of scientific publications have been focusing on LCA of building renovations, typically with a focus on improving the energy performance [7,8]. Several of these research studies have investigated the life-cycle efficacy of GHGe reductions in large-scale roll-outs of building stock renovations, on urban scale [9–11], national scale [12,13] or on European scale [14–16]. These stock-based studies typically investigate technical options for improving energy efficiency of the building stocks under investigation. However, building renovations from real-life cases are typically characterized by a multitude of additional criteria and desired functions aside from the technical focus on energy performance [17,18]. For instance related to accessibility, spatial organisation, or aspects of comfort other than thermal comfort [17,19]. Studies have shown that the contribution from e.g. office fit-outs can contribute to between 12-15% of initial embodied impacts [20]. The lack of knowledge about life-cycle impacts from energy efficiency measures versus measures for these other functions in real-life renovations constitutes a research gap for informed decision- and policy-making.

In parallel to the increased focus on renovations, ongoing policy development deals with performance evaluation and benchmarking of buildings. Benchmarking whole-life carbon for new construction and renovation has been recommended as a way to achieve net zero emissions [21]. Life cycle based GHGe have already become a part of building regulation in countries such as Denmark, France, Sweden and Finland, where some countries use benchmark as a minimum requirements in regulation [22]. Benchmarks can be based on either a bottom-up approach from, for instance, statistically derived data from case building, or follow a top-down approach based on e.g. political targets [23]. Benchmarks related to renovation are less frequent than for new construction, and benchmarks for renovation projects have both been defined as an equal value to new construction, and a different – lower – value [24]. For renovation projects, it has also been suggested to use benchmarks for building elements instead of whole building projects, and to make the benchmark based on the relation between embodied emissions and operational savings in the project [25].

1.1 Aim of study

Benchmarking renovation can be complicated due to the different functions of renovation projects. While the focus in most policy initiatives are on energy efficiency actions, the nature of adapting existing buildings, are not solely related to energy efficiency, but also to e.g. structure, interior design, occupant comfort etc. [19]. However, little is known about the actual impacts from a larger number of renovation cases, and what emissions are related to energy reduction and other added functions. Therefore, the aim of this study is to investigate the life cycle based GHGe from the multitude of changed functions in a larger sample of real-life renovation cases, using the Danish context as an example. Specifically, this study investigates:

1. What is the contribution from life-cycle embodied and operational GHGe in real-life renovation cases?
2. How much of the life-cycle embodied GHGe are caused by renovation actions specifically for reducing operational energy consumption in real-life renovations? and which building elements are of greater significance?
3. How does the insights from the cases contribute to discussions about different types of life-cycle GHGe benchmarks?

2 METHOD

This study of the GHGe of functions added in renovation projects is based on real-life cases in a Danish context. The renovation actions in the cases are categorized into different provided functions, to illustrate where the emissions in renovation projects come from.

2.1 Renovation cases

For the study, 23 Danish renovation cases have been collected with the purpose of showcasing the variation in GHG emissions of real-life renovation cases. The selection of cases is random, which therefore avoids systematic biases [26]. However, due to their sources, the cases represent a renovation subgroup of mainly larger renovation. The cases originate from three different sources: The sustainable certification scheme used in the Danish construction industry "DGNB" [27], cases collected from social housing projects, and other larger renovation projects that have been collected. Out of 23 cases, 21 of them are considered major renovations based on the building directive that defines major renovation as a change in more than 25% of the surface of the building envelope [1]. Certification is typically only done on large renovation cases, and the social houses and other projects also predominantly consist of larger physical changes.

The cases represent a variation of building types and types of intervention in renovations. The cases vary from entire conversions of the function of the building, to only smaller energy reduction actions. The renovation actions are described in table 1 and 2. The cases consist of 15 residential buildings, 4 offices, and 1 of each in the categories culture, hotel, hospital, and institution. Though the buildings represent a Danish context, the results will showcase if there are significant emission from other functions than energy reduction in real-life renovation cases. The trends in the Danish context will likely be similar in many other countries, however, this should be investigated further in future research.

Table 1: Description and categorisation of renovation cases.

Code	Building type	Conversion*	Description
C1	Cultural house	Conversion of production building into cultural building for sports, music etc.	Change of interior layout. Insulation of part of the ground floor slab and roof. Replacing and adding windows.
O1	Office	Conversion of production building into office	Change of interior layout. Insulation of ground floor slab, roof, and external walls. Adding new windows. Adding new building services for heating and water.
O2			Change of interior layout. Insulating roof and some external walls, replacing and adding new windows. Outside terrace. New building services for heating and cooling
O3		Conversion of education building into offices and retail	Change of interior layout. New façade, and insulation of roof. New roof terrace. New building services for water and ventilation.
O4		Conversion of a post office into offices and sport facilities	Change of interior layout. Adding new floor area and terrace on the roof. Insulation of external walls and roof. Adding new windows.
H1	Hotel	Conversion of production building into hotel	Adding floor area and terrace on top of the existing building. New interior layout. Insulation of roof. Replacing and adding windows. Structural support of the building. Replacing and adding building services for water, heating, and ventilation.
Hos1	Hospital		Change of interior layout, new roof, and new double-skin façade. Adding windows. Replacing building services for heating and ventilation.
I1	Institution	Conversion of an education building into childcare facilities	Change of interior layout, insulation of external walls and roofs, new ground floor slab, and replacement of windows. Adding roof terrace. Painting after sanitation. Replacing and adding building services for water, heating, and ventilation.
R1	Residential, single family		Change of interior layout. Replacement of ground floor slab and some exterior walls. Insulation in the roof, and replacements of windows. Replacing and adding building services for water, heating, and ventilation
R2	Residential, terraced houses		Some changes in interior layout. Replacement of windows. Replacing roofing material.
R3			Some changes in interior layout. Replacement of some of the foundation and columns in facade. Insulation of external walls, replacement of ground floor slab, and replacement of windows. Replacing and adding building services for water, heating, and ventilation
R4			Reducing the building area on the 1. floor. Combining apartments and changing layout. New balcony. Insulation of exterior walls and roof, and replacement of windows. New pergola outside. Replacing and adding building services for water, heating, and ventilation.
R5			Changing layout in some apartments. Insulation of external walls, and replacements of windows. Replacements of balconies. Replacing roofing material. Replacing and adding building services for heating and ventilation.
R6			Changing some internal layout and modernization including fire sections. Replacement of ground floor slab. Replacing and adding building services for water and ventilation
R7	Residential, multifamily	Conversion of an office building into student housing	Change of interior layout, new balconies, and replacement of windows. Replacing building services for water, heating, and ventilation.
R8			Changing layout in some apartments, replacing balconies, insulation of end walls, and new windows. Replacing building services for heating and ventilation
R9		Partial conversion: Conversion of garages into a common house.	Combining and changing sizes of apartments. Expansion of some balconies. Insulation of roof and external walls, New windows. New building services for heating and ventilation
R10			Insulating external walls and roof and ceilings facing unheated area. New windows. Expansion of balconies. Increase acoustics in slabs. New open façade at staircases.
R11			Change of layout in some apartments. Insulation of external walls, and new windows. New balconies. Adding some building services for heating, and ventilation.
R12			Combining apartments, insulating external walls and roof, and new windows. Replacing and adding building services for water, heating, and ventilation
R13		Conversion of attic into dwellings	Adding penthouses with balconies on top of the existing building. The renovation only considered the penthouses.
R14		Conversion of a cultural building into a residential building	Change of interior layout. Replacing and adding windows to improve daylight. Adding PV panels.
R15			Adding floor area on top and on one facade to expand existing apartments and improve daylight. Change of interior layout. New windows. Improving acoustics in floor slabs. Adding balconies.

* Changing the function of the building. Based on the definition in [19].

Table 2: Categorisation of renovation cases

Code	Decade of original construction	Gross floor area [m^2] (span)	Spatial	Layout	Energy reduction	Indoor climate	Fire	Structural	Contamination	Acoustics	Daylight	Outside areas	Elevators	Balconies	Local energy production	Replacements and repairs
C1	1970	1,000-5,000		X	X						X		X			
O1	1960	0-200		X	X	X					X					
O2	1960	5,000-10,000		X	X						X	X				X
O3	1950	10,000-20,000		X	X					X			X	X		X
O4	1970	10,000-20,000	X	X	X						X		X	X		
H1	1880/1960	10,000-20,000	X	X	X	X		X			X		X			X
Hos1	1980	5,000-10,000		X	X						X					X
I1	1910	1,000-5,000		X	X	X			X					X		
R1	1960	0-200		X	X	X										X
R2	1990	1,000-5,000		X	X											X
R3	1960	200-1,000		X	X	X		X								X
R4	1970	200-1,000	X	X	X	X						X		X		X
R5	1970	1,000-5,000		X	X	X										X
R6	1980	200-1,000		X	X	X	X									X
R7	2000	10,000-20,000		X	X					X			X	X		X
R8	1940	1,000-5,000		X	X								X	X		
R9	1990	1,000-5,000		X	X	X							X	X		X
R10	1972	>20,000**			X					X	X			X		X
R11	1950	5,000-10,000		X	X	X							X	X		X
R12	1940	1,000-5,000		X	X	X							X			X
R13	1930	200-1,000	X											X		
R14	1900	1,000-5,000		X	X						X		X		X	X
R15	1890	1,000-5,000	X	X	X					X	X			X		

** Consists of several stand-alone buildings

2.2 LCA procedure

Life cycle assessment (LCA) is performed on the renovation cases. The LCA has been performed in compliance with the standards for LCA on buildings, EN 15978 [6]. Impacts from new materials are included in the assessment, following the burden-free approach for existing materials [28]. The life cycles stages included are production (A1-3), replacements (B4), and waste processing and disposal (C3 and C4). Emissions from replacements are based on the service lives of buildings [29], and a reference study period of 50 years. The assessment is focused on the impact category “global warming potential” due to the political awareness.

Results are shown in the same unit, as is standard in climate declarations for new construction and current practice for renovation projects [30] in its national context. This is done to showcase results in the conditions they are currently being evaluated and compared. The unit is “kg CO_2-eq/m^2/year” with reference to the 50 year reference study period. The area used is the gross floor area for embodied impacts, and heated gross floor area for operational impacts. For the cases where area is added or removed during renovation, the area after renovation is used, in compliance with current practice.

2.2.1 Inventory for cases

The data reported by the data provider has been used for the building inventory such as drawings and descriptions or final inventories. The building parts included in the inventory consists of foundations, ground floor slab, external walls, roofs, windows and doors, internal walls, floor decks, stairs and ramps, Columns and beams, balconies, building services (water, ventilation, heating and cooling). This scope is respected across all the building cases, ensuring consistent comparison.

The operational energy used is made up by the energy demand calculations from buildings from heating, cooling, ventilation and hot water following the Danish building regulations [31]. Energy demand for lighting is also included in all other buildings than residential. The energy demand after renovation has been available for 15 of the 23 cases, whereas the energy demand before renovation has been available for 7 cases. The energy demand is calculated based on the heated floor area after renovation. For the 7 cases with data on energy demand before renovation, the same floor area was used, since there was no significant change in area during the renovation.

2.2.2 Environmental data and calculation tool

For the calculations the Danish national tool for LCA on buildings "LCAbyg" is used [32–35]. LCAbyg uses environmental data that is considered representative for the Danish context. It consists of generic data from the German Ökobaudat database [36], and some environmental product declarations (EPD's). Additional EPD's for specific products have been added in the cases. All data follow EN15804 [37]. Emissions from the Danish national energy system is used for the operational energy emissions [38] which is based on data from a consultant and the Danish energy agency [39,40]. This data includes projected decarbonisation of the energy system based on political targets at the time they were created.

2.3 Categorizing functions in renovation

Renovation project can add new function or provide improvements to existing function, such as improving the insulation properties of the building to reduce energy use. Though energy reduction is a large focus in renovation cases, new materials also go towards other functions in the renovation. This section explains the categorisation that was made to illustrate the different functions provided by renovation projects.

Table 3 shows a list of functions used in this study to categorize the emissions from the different materials in renovation projects. The list is based on functional demands from the Danish building code [31]. Additionally, the list also includes the functions "spatial" and "balcony". The first is added to show the emissions from increasing or reducing the building floor area, and the latter is added to show emissions from adding balconies as this was included in several of the cases.

Table 1 shows which cases contribute to the different functions. The table shows that most cases change the interior layout and include actions to reduce energy use. Five cases include an extension, and one case removed some building area, which is all categorized in the "spatial" function. The indoor climate function includes emission from ventilation and floor heating systems that have been implemented. This applies for several of the residential buildings where implementing ventilation is part of the renovation and for buildings that are converted to a different use. Terraces and balconies are added to the "balcony" function, which is added to several of the buildings.

The functions from new materials will in some cases overlap. For instance, fire and acoustic is considered in many building products that are added in renovation, however, the categories have not been used much in this study. This is because the categorisation only considers the primary function of the renovation action based on what the purpose of the renovation action was. This is determined based on the available knowledge on the project. If we consider acoustic ceilings, they will often be categorised with the "layout" function, because the ceilings are changed together with other interior elements as part of the change in layout. Furthermore, while windows are associated with daylight, the majority of new windows has not been categorised in "daylight", but rather in the "energy reduction" category. This is because they contribute to significant energy reductions. The "daylight" category is only used when more daylight is added by making new openings in the building where there weren't any before. Building services have been categorized into several different categories such as "indoor climate", when ventilation and floor heating are introduced, though this also has an influence on the building's energy use. Building services are categorized in the "spatial" category when they are related to building extensions.

Table 3: List of functions added in the renovation.

Renovation function	Description
Spatial	Components that are added to increase or reduce the floor area of the building.
Layout	Components that are added or changed due to changes in the interior layout. Includes new floor and ceilings even if this could be due to ended service life or aesthetic purposes etc.
Energy reduction	When a component in the building envelope is replaced or insulated or e.g. ventilation systems are replaced to reduce energy use and replacement of hot water tank.
Indoor climate	e.g. introducing mechanical ventilation or floor heating, if this was not here before.
Fire	Components added or changed to comply with building code on fire safety.
Structural	Components added or changed to comply with building code on load-bearing structures.
Contamination	Components added or changed with the main focus to remove contaminated materials.
Acoustics	Components added or changed with the main focus to increase acoustic properties in the building.
Daylight	Components added or changed in relation to daylight. E.g. increasing façade openings to enhance daylight.
Outside areas	Components added or changed outside the building.
Elevators	Components added or changed when an elevator is added, where there were no elevators before
Balconies	Components added or changed when a balcony is added, where there was no balcony before
Local energy production	Energy production on site, such as PV-panels
Replacements and repairs	Replacements or repairs with no significant added or improved function such as replacing water and waste piping.

3 RESULTS

The result section show GHGe from the 23 renovation cases with a focus on the contribution from energy reduction versus other provided functions in the building. This information is relevant to understand how emissions in renovation projects can be reduced.

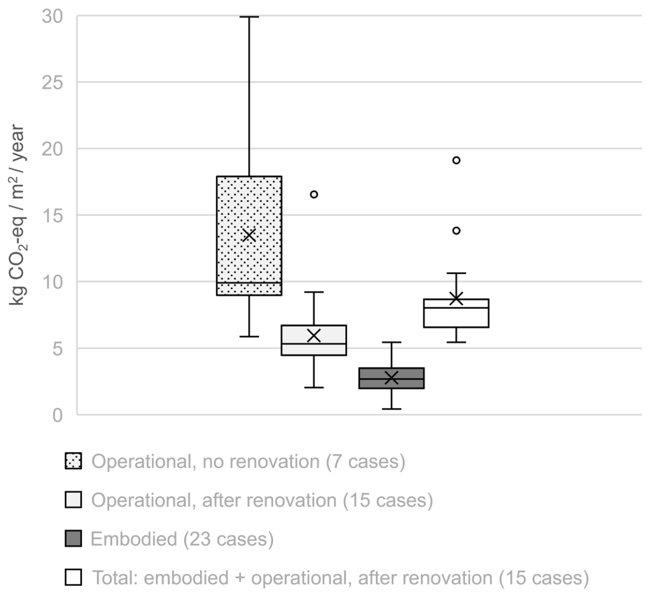
3.1 Embodied and operational impacts

The GHGe from renovation projects are shown in figure 1, where the specific available data going into the graph is shown in the table. The contributions from operational energy use are shown both before and after renovation, where average values are 13.5 kg CO_2-eq/m^2/year and 6.0 kg CO_2-eq/m^2/year, respectively. The "before" considers a scenario where the building is not renovated, thus the previous energy demand of the existing building is considered over the RSP. For the cases, where data was available both before and after renovation, a potential impact savings can be considered. The savings in GHGe for operational energy use from the renovation is between 20% and 65% savings (average approximately 50 % savings).

There is a large variation of the operational emissions, especially "before" renovation. This partially reflect the variation of the energy performance of the buildings both before and after renovation, but for some of the cases there is also a difference in the thermal energy technologies. For heating, most cases are supplied by district heating, where the incineration of waste and biomass in combined heat and power plants are large contributors to the Danish district heating [39]. However, for the cases I1 and R1, the heating is supplied solely by natural gas. Natural gas has significantly higher emissions per kWh, which is reflected in the higher emissions.

The embodied emissions over the life cycle of the renovation are shown in figure 1 for all the 23 cases. The embodied emissions also vary but has an average value of 2.8 kg CO_2-eq/m^2/year, which is lower than the operational emission and savings. The reason for the variance in embodied emissions will be investigated in the next section.

The average total emissions, from operational and embodied emissions after renovation, are 8.7 kg CO_2-eq/m^2/year, however, emissions span from 5.4 to 19.1 kg CO_2-eq/m^2/year.



	C1	O1	O2	O3	O4	H1	Hos1	I1	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
⊞				9.9					29.9		17.9		9.0	5.9				9.7		12.1			
□			5.3	3.6			5.2	9.2	16.5		6.8		5.8	4.7	4.5	6.7	4.5	6.2		5.5	2.0	2.7	
■	2.0	5.4	1.2	2.5	1.1	2.8	3.0	4.6	2.6	0.4	3.9	4.2	2.4	2.0	2.0	1.3	2.7	2.2	3.0	3.1	5.1	2.7	3.5
□			6.6	6.1			8.2	13.8	19.1		10.6		8.2	6.7	6.5	8.0	7.2	8.4		8.7	7.1	5.4	

Figure 1: Embodied and operational GHG emissions for the renovation cases over 50 years. The figure also shows the operational emissions over 50 years if the building hadn't been renovated. The boxplot shows the median and mean values, upper and lower quartiles, minimum and maximum and outliers in the dataset. The table shows the datasets that were included.

3.2 Embodied impacts from provided functions

To understand the variation in embodied impacts presented in the previous section, this section will investigate the source of emissions, in terms of the function the materials provide to the building. From this, we can see which embodied impacts come from energy reduction actions, and which are due to other added functions.

Figure 2a shows emissions from the renovation cases divided into the provided functions. The cases show a variation in the emission from functions, which is illustrated in figure 2b. Figure 2b shows median and average emissions are highest for the functions spatial, layout and energy reduction. However, "spatial" only appears in five of the 23 cases, whereas layout and energy reduction appear in almost all cases (21 and 22 cases, respectively). Therefore, considering the emissions across all cases, "spatial" only contribute to 8%, on average, whereas "energy reduction" contribute to 43% followed by 18% from "layout". Other function categories that appear with high frequency and substantial emissions are indoor climate, daylight, elevator, balconies, and "replacements or repairs". Local renewable energy supply (in this case PV panels) only appears in one case but has a significant influence on emissions. If the PV panels are considered together with the "energy reduction" category (since they both reduce operational energy emissions) they contribute to a total of 46 % of embodied emissions, on average.

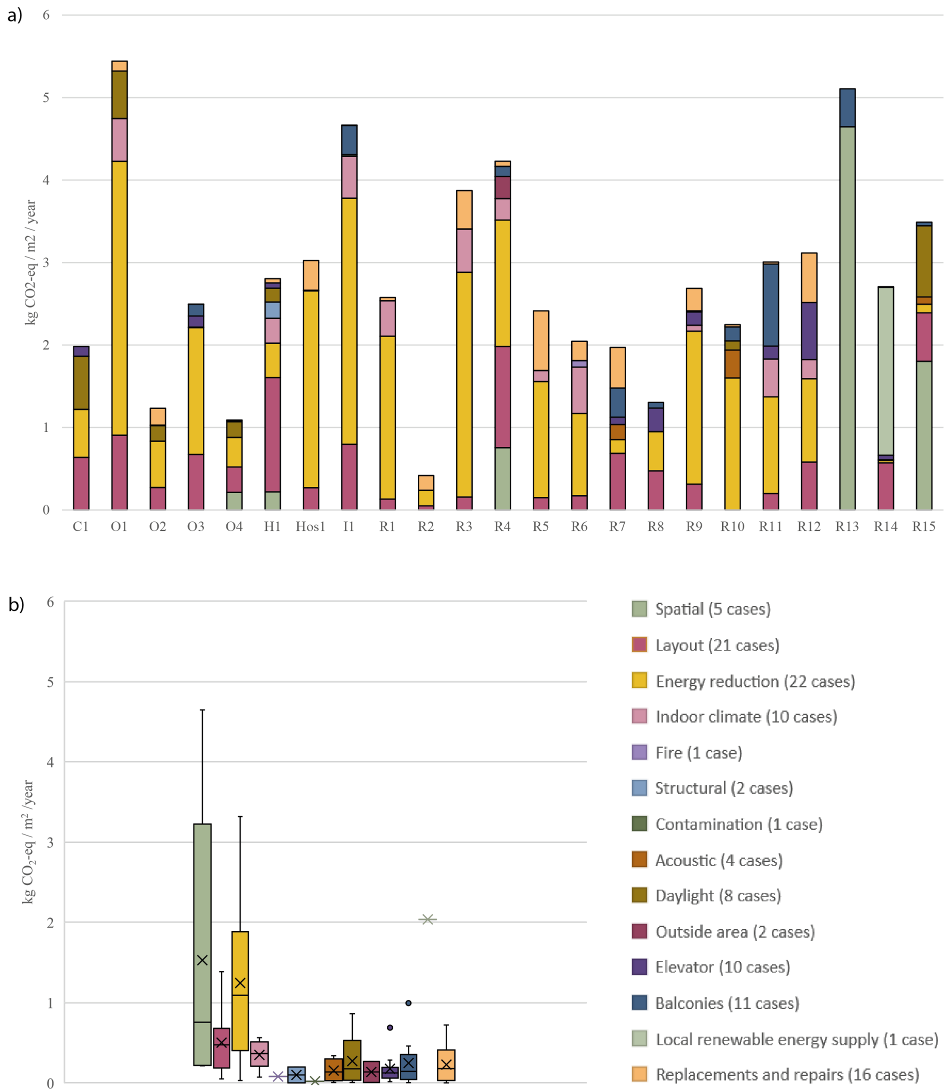


Figure 2: a) Embodied emissions from renovation cases devided into contributions from functions. b) Variance of function in embodied emissions described through a boxplot that shows the median and mean values, upper and lower quartiles, minimum and maximum and outliers in the dataset.

Though "energy reduction" contribute to largest emissions on average, figure 2a shows that some of the cases predominantly have emissions from other functions. This applies for the cases H1, R7, R13, R14, and R15. The cases H1 and R7 are both conversions and have the largest emissions from layout, from changing the building function. R13 and R15 add a completely new area to the existing structure, thus their largest emissions come from the spatial category. R14 is mainly a change in layout but adds PV panels, which have a significant influence on embodied emissions.

The five cases behind the most profound embodied emissions (>3.5 kg CO_2-eq/m^2/year) are the cases O1, I1, R3, R4, and R13. These cases have different building typology and functions, however, 3 of the 5 buildings converts the building use: O1 is a production building turned into office, I1 is an education building turned into office, and R13 is an attic turned into dwellings. R13 is different, as it only includes the attic area, which is remade, and converted into dwellings. Therefore, most emissions go to the "spatial" category, as dwelling area has been added, e.g. by constructing an entirely new roof. The remaining two cases (R3 and R4) are residential buildings renovated for energy and interior layout.

The cases with lowest embodied emissions (<1.5 kg CO_2-eq/m^2/year) are the cases O2, O4, R2, and R8. Again, the building types are different (both residential and office). The case O2 only has limited interventions in the building envelope due to architectural considerations. For the case O4, the existing energy use conditions were good, therefore the interventions for this case are also limited, with more focus on the interior layout. The cases R2 and R8 both only include limited interventions, where R8 focus on the interior layout of some apartments, and balconies.

3.3 Energy reduction measures - building element level

For future emission savings in the renovation, it is relevant to understand from which building elements the emissions originate, and the difference in building elements between considering impacts from energy reduction alone, and the total embodied emissions.

The previous section showed that emissions related to energy reductions make up 43 % of the embodied emissions, on average. Figure 3a illustrates which building elements these emissions are attributed to, for the different cases. The figure shows that 20 out of 23 cases have energy reduction measure from "windows, doors and glazing systems", with an average contribution of 0.41 kg CO_2-eq/m^2/year. The emissions mainly come from replacing the existing windows with new ones. Only 9 cases contribute to the ground floor slabs, but the average emission are higher, at 0.72 kg CO_2-eq/m^2/year. Insulating the ground floor slab typically requires that the entire element is replaced, thus contributing with high emissions from new concrete and rigid insulation materials. External walls and roofs also contribute significantly to emissions from energy reduction. This is typically from adding insulation, and associated materials, to the existing elements.

Figure 3b illustrate the impact variation from building elements for energy reduction measures, and figure 3c shows the variation for total embodied emissions. Comparing figure 3b and 3c, shows that the boxplot for the building elements windows, ground floor slabs, roof, and external walls, do not change significantly (change of average value between 3-24%) between the two boxplots. Therefore, majority of emissions from these building elements can be ascribed to energy reductions. The changes that do appear are for instance in the ground floor slab where average and median values are reduced in figure 3b due to smaller renovation measures related to other function, such as new flooring. For other building elements such as internal walls, floor decks, balconies and building services, the emissions come from other functions. For instance, the building services have a significant influence. The emissions from building services are ascribed to several different function categories such as "energy reduction", "elevators", "indoor climate", "spatial", "replacement and repair", and "local renewable energy".

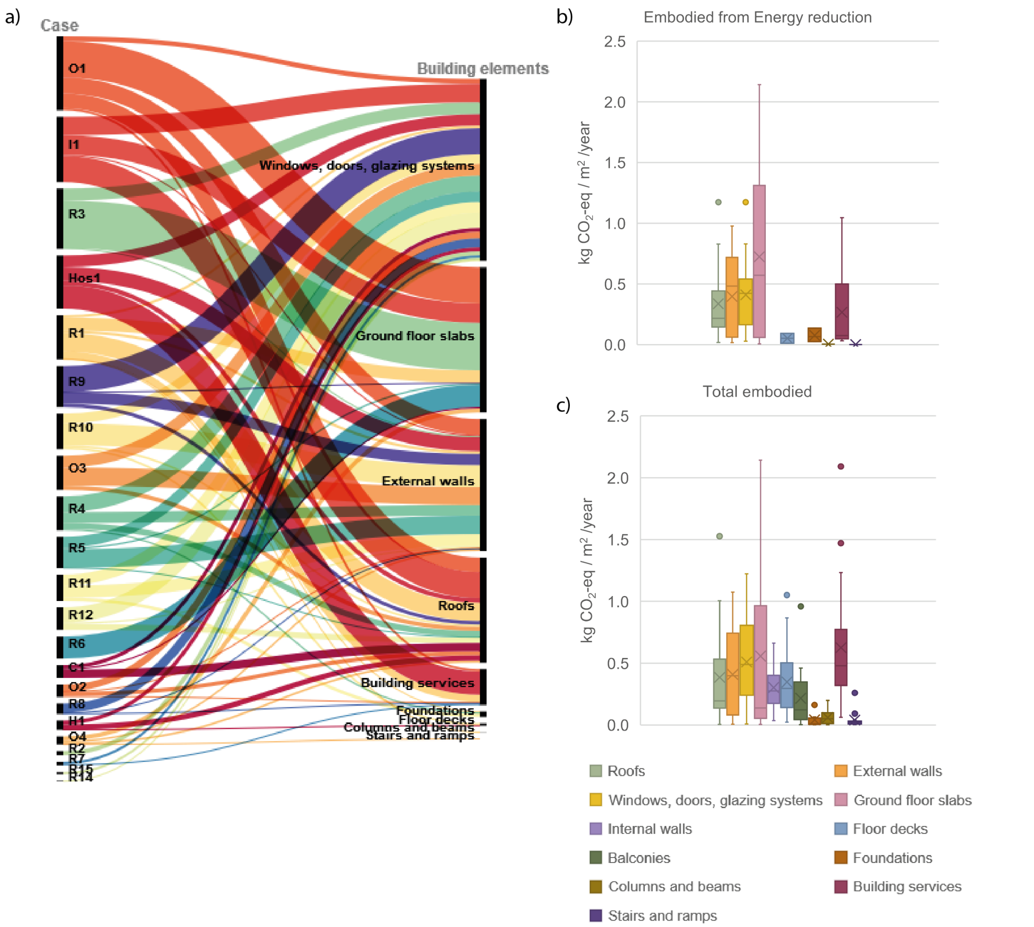


Figure 3: Embodied GHG emissions from energy reduction measures for a) contribution from cases and building elements, and b) variation of building elements compared to total embodied emissions for all functions.

4 DISCUSSION

Results showed how renovation projects contribute to a multitude of new functions in renovation, including operational energy savings. For future policymaking it should be considered if and how the different functions should be evaluated in the assessment of GHG emissions in renovation. Though the cases in this study does not represent all types of renovation cases, the emissions from function can provide an insight into the possible hotspots which can be addressed in future design and legislation. For instance, if legislation solely focuses on energy reduction actions, then the results across building types showed that a significant part of embodied emissions will be neglected. Energy reduction actions in this study show net savings considering both embodied and operational impacts, which is consistent with a review of previous literature [8]. However, a multitude of existing literature shows that further savings are possible by considering material choices and design in energy reduction actions [41–46]. Reducing embodied impacts from energy reduction actions should therefore also be considered in future policymaking.

4.1 Uncertainty of operational emissions

Emissions from operational energy can vary a lot depending on different factors, such as local climate conditions, and the energy sources, and future scenarios. For the energy source, the results showed significantly larger emissions from the buildings supplied with natural gas for heating than the buildings using district heating. Energy technologies are largely dependent on national energy strategies, which are expected to reduce GHGe from the energy grid in Europe in the coming years [2]. GHGe savings in operational energy from energy renovation will therefore become less significant in the future. Furthermore, it is important to consider the temporal differences between upfront embodied emissions, and the operational energy reduction, which happen over time. Reducing upfront emissions is important to stay within our carbon budget to keep temperature rise well below two degrees Celsius as stated in the Paris agreement [48].

4.2 Considerations for benchmarks

Results in this study showed large variations in emissions in renovation projects due to differences in provided functions. The differences were visible, even though 21 of 23 cases are considered major renovation, following the definition based on changes in the building envelope in the EPBD [1]. This is caused by differences in existing conditions of the building, and the considerations for future use of the building. Consequently, different functions are provided within the projects.

Most radically, benchmarks can decide what functions are truly necessary to meet our needs, thus limiting emissions to those functions [49]. For instance, building expansions may be needed to provide shelter for more people which solves an immediate need. However, it can also be used to expand the living area for the current inhabitants, which only continues the growing rise in living area per person in Denmark [50]. Further, layout changes can sometimes be necessary to secure the future use of the building [19]. Balconies, improvements in indoor climate, and daylight contribute to the wellbeing of the inhabitants. On the other end of the spectrum, benchmarks values can be used simply to limit emissions from the function by optimizing design and material choices, not to limit the functions themselves.

Benchmark values for renovation has been suggested as a) a single benchmark for the whole renovation project, b) for building elements, or c) based on the relation between embodied emissions and operational savings in the project [25]. Benchmark a) for the entire renovation project is commonly used for new construction, however, renovation projects are more unique due to the different initial conditions and the variety of scale and functions provided in a renovation project This makes them difficult to benchmark on a building level using a single value. An exception to this is the building extensions, which is similar to new construction, and contributed to significant impacts in several of the cases from the "spatial" category. Building extensions pose a methodological challenge in terms of what area emissions are allocated to. The results in this study reflect the new functional equivalent, where emissions are normalised to the floor area *after* renovation, including both the extension and the existing building. However, if building extensions are to be benchmarked separately from the existing building, embodied and operational emissions would have to be allocated to the new area.

Benchmarks values can also be defined on a smaller scale such as the building elements or product scale (suggestion b), where the function is similar to new construction e.g. emission per m^2 wall. Results showed that some of the elements that contributed the most to embodied GHGe in the renovation projects were from building envelope elements, followed by building services, internal walls, floor decks, and balconies. In the renovation actions, the windows and ground floor slabs were mainly replaced. They are therefore entirely new elements, where element benchmarks can be considered similar to new construction, whereas the renovation measure for roofs and external walls are mainly changes in existing elements making it more difficult to set generic benchmarks. Benchmarks for building elements do not give any indication of how the entire project performs.

A benchmark that considers the relation between embodied emissions and operational savings in the renovation project (suggestion c) can be relevant when considering the emissions related to energy reduction. However, results in this study showed that majority of embodied emissions were not done specifically for energy reductions. Emissions that consider other functions such as layout, can provide social (comfort, aesthetic etc.) and economic sustainability of the building [19], and thus future-proofs the building in relation to e.g. demolition. For emissions related to these functions, it can therefore be relevant to consider other benchmarks related to e.g. human and social needs.

4.3 Limitations of the study

The study is a preliminary study in the Danish context for building renovation projects. The study considers a large number of cases. However, for generalisation, the number of cases is still limited, especially due to the varied nature of renovation projects. The study consists of mainly residential buildings, which is supplemented with some offices and other building types. However, general trends are visible across all building types, such as the significance of considering embodied emissions from “other functions” than energy reduction. However, future studies should be conducted to investigate if this applies for other contexts as well. Further, it should investigate the significance of building types and renovation types.

The categorisation of functions is based on determining the main function of the renovation action. As renovation actions can contribute to several functions, the results will reflect some bias in the choice of category.

The results were normalized to a reference study period (RSP) of 50 year, reflecting the current practice for the Danish context, which uses the same RSP for new construction and renovation. Using identical RSP’s for new construction and renovation is also the most common in practice and literature [52]. For the calculation, the required/estimated service life of the renovation projects are assumed identical to the RSP. However, this approach is debatable as the service life of renovation projects can depend on the condition of the building, the type of renovation etc. [52]. The cases in this study undergoing only smaller renovations may therefore also have a shorter service life, and would thus perform worse, if this had been considered in the assessment. For legislation, a unified approach with the same RSP and service life of the renovation projects can therefore be misleading, if the service lives of the projects are very different.

5 CONCLUSIONS

Findings from this study show, that in the renovation cases where before- and after energy demand were reported, life-cycle GHGe-savings of around 50% were obtained, reducing operational emissions from 13.5 kg CO_2-eq/m^2/year to 6.0 kg CO_2-eq/m^2/year on average. Despite uncertainties and variations in-between the cases, these numbers from the real-life renovation cases suggest, as other studies before, that substantial reductions of operational emissions can be achieved in a life-cycle perspective on renovations. The energy and emissions savings are an important part of fulfilling the goals of the Renovation Wave under the European Green Deal. However, this study expands the existing knowledge about life-cycle GHGe of renovations by systematically assessing the building functions improved or established in executed renovations in the Danish context. In the 23 renovation cases an average of 2.8 kg CO_2-eq/m^2/year is ascribed to the material-related, embodied GHGe. A remarkable 54% of these life-cycle embodied impacts from the renovation cases are associated with functions that are not related to improving energy efficiency, but to other aspects such as spatial adjustments, interior layout changes or establishment of balconies. Of the 46% embodied GHGe associated with improved energy efficiency, almost 1/3 came from the renovation of windows and glazing systems, a renovation action that all modelled cases employed. Less frequent, in 6 cases, was the renovation of ground floor slabs. However, on a per-case basis, this renovation action was notably emission intense, typically representing around 30%-70% of the embodied GHGe associated with the energy efficiency measures of the cases in question.

The growing interest in benchmarking and regulating the life-cycle GHGe from renovations makes it more important to recognize the multitude of purposes and functions in play within real-life renovations. Literature has suggested three main approaches to benchmark renovation projects. These approaches are each challenged by the complex characteristics of renovations, as indicated by the results of this study:

1. Single benchmark for the whole building. The results in this study showed that projects varied significantly in embodied and operational emissions, even though 21 out of the 23 cases are considered major renovations following the EPBD definition. This means that it will be very difficult to find a common benchmarking system to encompass the variation.

2. Benchmarks on a smaller, material scale, such as the building element level. This study provides pointers to the significance of these elements in the building envelope for further exploration.

3. Benchmark of renovations based on their GHGe "savings" from energy reduction. Results from this study clearly shows that renovation projects contribute to a multitude of functions other than energy reduction. In theory, a system of allocating emissions as per functions, as done in this study, could tackle this. However, a such categorization would be difficult to integrate into practice, due to the high requirements for documentation.

Despite large variation across real-life renovation cases, the study clearly illustrates the significance of embodied emissions related to a variety of new functions beyond energy efficiency across the cases. This knowledge is important for the future benchmarking of renovation projects.

AUTHOR CONTRIBUTIONS

Regitze Kjær Zimmermann: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Visualization; Writing - original draft **Freja Nygaard Rasmussen**: Conceptualization; Supervision; Writing - review & editing **Harpa Birgisdóttir**: Supervision; Writing - review & editing; Funding acquisition

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper..

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References

[1] European Commission, Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast), Off. J. Eur. Union. 0426 (2021) 10–27. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889.

[2] European Commission, Renovation Wave for Europe - greening our buildings, creating jobs, improving lives, Off. J. Eur. Union. (2020) 26. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662.

[3] N.M.P. Bocken, I. de Pauw, C. Bakker, B. van der Grinten, Product design and business model strategies for a circular economy, J. Ind. Prod. Eng. 33 (2016) 308–320. https://doi.org/10.1080/21681015.2016.1172124.

[4] European Commission, European Green Deal, 2019. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#documents.

[5] European Commission, European Climate Law, 2021. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119.

[6] CEN, EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, 2012. https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/.

[7] O. Fahlstedt, A. Temeljotov-Salaj, J. Lohne, R.A. Bohne, Holistic assessment of carbon abatement strategies in building refurbishment literature — A scoping review, Renew. Sustain. Energy Rev. 167 (2022) 112636. https://doi.org/10.1016/j.rser.2022.112636.

[8] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life cycle assessment (LCA) of building refurbishment: A literature review, Energy Build. 135 (2017) 286–301. https://doi.org/10.1016/j.enbuild.2016.11.042.

[9] E. Verellen, K. Allacker, Life cycle assessment of clustered buildings with a similar renovation potential, Int. J. Life Cycle Assess. 27 (2022) 1127–1144. https://doi.org/10.1007/s11367-022-02095-0.

[10] X. Yang, M. Hu, C. Zhang, B. Steubing, Key strategies for decarbonizing the residential building stock: Results from a spatiotemporal model for Leiden, the Netherlands, Resour. Conserv. Recycl. 184 (2022) 106388. https://doi.org/10.1016/j.resconrec.2022.106388.

[11] N. Cihan Kayacetin, A. Versele, A Circular and Bio-based Renovation Strategy for Low-income Neighbourhoods, IOP Conf. Ser. Earth Environ. Sci. 1078 (2022). https://doi.org/10.1088/1755-1315/1078/1/012080.

[12] K. Kertsmik, K. Kuusk, K. Lylykangas, T. Kalamees, Evaluation of renovation strategies: cost-optimal, CO_2e optimal, or total energy optimal, or total energy optimal, Energy Build. 287 (2023) 112995. https://doi.org/10.1016/j.enbuild.2023.112995.

[13] A. Lupíšek, T. Trubačík, P. Holub, Czech building stock: Renovation wave scenarios and potential for CO2 savings until 2050, Energies. 14 (2021). https://doi.org/10.3390/en14092455.

[14] D.A. Pohoryles, C. Maduta, D.A. Bournas, L.A. Kouris, Energy performance of existing residential buildings in Europe: A novel approach combining energy with seismic retrofitting, Energy Build. 223 (2020) 110024. https://doi.org/10.1016/j.enbuild.2020.110024.

[15] K.N. Streicher, M. Berger, E. Panos, K. Narula, M.C. Soini, M.K. Patel, Optimal building retrofit pathways considering stock dynamics and climate change impacts, Energy Policy. 152 (2021) 112220. https://doi.org/10.1016/j.enpol.2021.112220.

[16] F. Pittau, G. Habert, G. Iannaccone, A Life-Cycle Approach to Building Energy Retrofitting: Bio-Based

Technologies for Sustainable Urban Regeneration, IOP Conf. Ser. Earth Environ. Sci. 290 (2019). https://doi.org/10.1088/1755-1315/290/1/012057.
[17] N. Galiotto, P. Heiselberg, M.-A. Knudstrup, Integrated Renovation Process: Overcoming Barriers to Sustainable Renovation, J. Archit. Eng. 22 (2016) 1–12. https://doi.org/10.1061/(asce)ae.1943-5568.0000180.
[18] P.A. Jensen, E. Maslesa, J.B. Berg, Sustainable building renovation: Proposals for a research agenda, Sustain. 10 (2018). https://doi.org/10.3390/su10124677.
[19] S. Shahi, M. Esnaashary Esfahani, C. Bachmann, C. Haas, A definition framework for building adaptation projects, Sustain. Cities Soc. 63 (2020) 102345. https://doi.org/10.1016/j.scs.2020.102345.
[20] A. Ghose, S.J. McLaren, D. Dowdell, R. Phipps, Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand, Build. Environ. 117 (2017) 274–287. https://doi.org/10.1016/j.buildenv.2017.03.012.
[21] BPIE (Building Performance Institute Europe), Roadmap To Climate-Proof Buildings and Construction - How To Embed Whole-Life Carbon in the Epbd, 2022. https://www.bpie.eu/publication/roadmap-to-climate-proof-buildings-and-construction-.
[22] OneClickLCA, Construction Carbon Regulations In Europe, 2022. https://www.oneclicklca.com/construction-carbon-regulations-in-europe/.
[23] ISO, ISO 21678:2020 Sustainability in buildings and civil engineering works – Indicators and benchmarks – Principles, requirements and guidelines, 2021. https://www.iso.org/standard/71344.html.
[24] T. Lützkendorf, M. Balouktsi, Benchmarking and target-setting for the life cycle-based environmental performance of buildings, 2023. https://annex72.iea-ebc.org/Data/publications/EBC_Annex_72_Benchmarking_for Environmental_Performance_of_Buildings_2023.pdf.
[25] A. Lund, R. Zimmermann, J. Kragh, J. Rose, S. Aggerholm, H. Birgusdottir, Klimapåvirkning fra renovering: Muligheder for udformning af grænseværdier til LCA for renovering, 2022. https://vbn.aau.dk/en/publications/klimapåvirkning-fra-renovering-muligheder-for-udformning-af-græns.
[26] B. Flyvbjerg, Five Misunderstandings About Case-Study Research, Qual. Res. Pract. (2011) 390–404. https://doi.org/10.4135/9781848608191.d33.
[27] Rådet for bæredygtigt byggeri, DGNB, (2023). https://rfbb.dk/dgnb-certificering (accessed June 30, 2023).
[28] R.K. Zimmermann, F.N. Rasmussen, K. Kanafani, L.C. Malabi Eberhardt, H. Birgisdóttir, Reviewing allocation approaches and modelling in LCA for building refurbishment, IOP Conf. Ser. Earth Environ. Sci. 1078 (2022). https://doi.org/10.1088/1755-1315/1078/1/012095.
[29] K. Haugbølle, V. Mahdi, M. Morelli, H. Wahedi, BUILD Levetidstabel, Copenhagen, 2021. https://build.dk/Pages/BUILD-levetidstabel.aspx.
[30] S. Butera, A.A.W. Karl, T.F. Astrup, C. Collin, N.L. Rasmussen, J.R. Nielsen, L.H.H. Sørensen, Klimavenligt byggeri og LCA - Analyse af udvalgte landes tilgange til klimavenligt byggeri, LCA og samfundsøkonomi, 2021. https://www.lifecyclecenter.se/wp-content/uploads/Analysis-of-other-countries-approach-to-building-LCA.pdf.
[31] Danish housing and planning authority, Danish Building Regulations, (2023). https://bygningsreglementet.dk/ (accessed February 28, 2023).
[32] F.N. Rasmussen, H. Birgisdóttir, Development of the LCAbyg tool: influence of user requirements and context, in: C. ZEBAU – Centre for Energy Architecture and the Environment GmbH (Ed.), 2016. https://doi.org/10.5445/IR/1000051699.
[33] K. Kanafani, R.K. Zimmermann, F.N. Rasmussen, H. Birgisdóttir, Learnings from developing a context-specific LCA tool for buildings—the case of lcabyg 4, Sustain. 13 (2021) 1–23. https://doi.org/10.3390/su13031508.
[34] R.K. Zimmermann, K. Kanafani, F. Nygaard Rasmussen, H. Birgisdóttir, Early Design Stage Building LCA using the LCAbyg tool: Comparing Cases for Early Stage and Detailed LCA Approaches, IOP Conf. Ser. Earth Environ. Sci. 323 (2019). https://doi.org/10.1088/1755-1315/323/1/012118.
[35] K. Kanafani, R.K. Zimmermann, F.N. Rasmussen, H. Birgisdóttir, Early Design Stage Building LCA using The LCAbyg Tool: New Strategies For Bridging The Data Gap, IOP Conf. Ser. Earth Environ. Sci. 323 (2019).

https://doi.org/10.1088/1755-1315/323/1/012117.
[36] Ökobaudat, Ökobaudat, (2023). https://www.oekobaudat.de/ (accessed June 7, 2023).
[37] CEN, EN 15804+A1 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, 2012. https://webshop.ds.dk/en/standard/M254454/ds-en-15804-2012.
[38] The Danish building code, Emissions from electricity, district hearing, and natural gas, (2023). https://bygningsreglementet.dk/Bilag/B2/Bilag_2/Tabel_8#1f165e42-7a97-45dd-9f4d-5b6373522e23 (accessed June 7, 2023).
[39] COWI, Opdaterede emissionsfaktorer for el og fjernvarme, 2020. https://bpst.dk/da/Byggeri/Lister/Publikationsliste?theme=Indeklima.
[40] Danish Energy Agency, Klimastatus og -fremskrivning 2021, 2021. https://ens.dk/service/fremskrivninger-analyser-modeller/klimastatus-og-fremskrivning-2023.
[41] X. Su, Z. Luo, Y. Li, C. Huang, Life cycle inventory comparison of different building insulation materials and uncertainty analysis, J. Clean. Prod. 112 (2016) 275–281. https://doi.org/10.1016/j.jclepro.2015.08.113.
[42] J. Sierra-Pérez, J. Boschmonart-Rives, X. Gabarrell, Environmental assessment of façade-building systems and thermal insulation materials for different climatic conditions, J. Clean. Prod. 113 (2016) 102–113. https://doi.org/10.1016/j.jclepro.2015.11.090.
[43] M. Braulio-Gonzalo, M.D. Bovea, Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimisation, Energy Build. 150 (2017) 527–545. https://doi.org/10.1016/j.enbuild.2017.06.005.
[44] H. Huang, Y. Zhou, R. Huang, H. Wu, Y. Sun, G. Huang, T. Xu, Optimum insulation thicknesses and energy conservation of building thermal insulation materials in Chinese zone of humid subtropical climate, Sustain. Cities Soc. 52 (2020) 101840. https://doi.org/10.1016/j.scs.2019.101840.
[45] J. Carreras, D. Boer, G. Guillén-Gosálbez, L.F. Cabeza, M. Medrano, L. Jiménez, Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact, Energy Build. 88 (2015) 335–346. https://doi.org/10.1016/j.enbuild.2014.12.007.
[46] B. Nicolae, B. George-Vlad, Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving, Energy Build. 86 (2015) 74–85. https://doi.org/https://doi.org/10.1016/j.enbuild.2014.10.021.
[47] IEA, Key energy statistict, (2020). https://www.iea.org/countries/denmark (accessed July 23, 2023).
[48] UN, The Paris Agreement, (2023). https://unfccc.int/process-and-meetings/the-paris-agreement.
[49] M. Heide, M.Z. Hauschild, M. Ryberg, Reflecting the importance of human needs fulfilment in absolute sustainability assessments: Development of a sharing principle, J. Ind. Ecol. 27 (2023) 1151–1164. https://doi.org/https://doi.org/10.1111/jiec.13405.
[50] Statistics Denmark, Housing, (2023). https://www.dst.dk/en/Statistik/emner/borgere/boligforhold (accessed July 29, 2023).
[51] R.K. Zimmermann, Z. Barjot, F.N. Rasmussen, T. Malmqvist, M. Kuittinen, H. Birgisdottir, GHG emissions from building renovation versus new-build : incentives from assessment methods, Build. Cities. 4 (2023) 274–291. https://doi.org/10.5334/bc.325.
[52] Y. Decorte, N. Van Den Bossche, M. Steeman, Guidelines for defining the reference study period and system boundaries in comparative LCA of building renovation and reconstruction, Int. J. Life Cycle Assess. (2022). https://doi.org/10.1007/s11367-022-02114-0.

Appendix B. Publication II

Publication II: **GHG emissions from building renovation versus new-build: incentives from assessment methods**. Zimmermann, R. K., Barjot, Z., Rasmussen, F. N., Malmqvist, T., Kuittinen, M., & Birgisdottir, H. In Buildings and Cities, 2023, 4 (1), pp 274-291

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GHG emissions from building renovation versus new-build: incentives from assessment methods

SPECIAL COLLECTION: UNDERSTANDING DEMOLITION

RESEARCH

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ABSTRACT

A variety of life cycle assessment (LCA) calculation methods and rules exist in European countries for building performance evaluation based on new-build. However, the increased focus on the retention and renovation of the existing building stock raises questions about the appropriateness of these the methods and rules when applied to renovation cases. Using a real renovation case, Danish, Finnish and Swedish LCA-based greenhouse gas emissions (GHGe) assessments are assessed for how they position building renovation in relation to demolition and new-build reference values. The influence of these three different methods is examined for future development policies. Results show that upfront emissions for renovation are significantly lower for all approaches. The Swedish approach had the lowest GHG emissions compared with a scenario with demolition and new-build due to the method, which only includes upfront emissions of new materials. The Danish and Finnish renovation cases each performed worse in comparison with the new-build future emissions, specifically from operational energy use. Therefore, method development should consider incentives for upfront and future emissions. Furthermore, methods could account for the existing materials in the building, which are included in the Danish and Finnish approaches. This would provide incentive for renovation and reuse.

POLICY RELEVANCE

Future policymaking needs to consider the influence of LCA methods on climate impact assessment of building renovations. The temporal differences occur when renovation is compared with demolition and new-build. Policy needs to take account of these temporal differences for apportioning GHG emissions between upfront and future emissions. A key question is whether existing materials should be included in the assessment as this would incentivise the reuse of these materials. Differences in accounting for the impacts of biogenic carbon in materials yields different results. This is a key issue in carbon accounting and will influence future practice.

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1. INTRODUCTION

The construction and operation of buildings are using vast amounts of resources and are accountable for 38% of greenhouse gas emissions (GHGe) globally (UNEP 2020). Hence, building and construction activities are important to reach policy targets for climate as well as circular material use (Giesekam *et al.* 2018). In recent years, climate considerations for buildings have expanded beyond operational energy use to include the embodied impacts of buildings. This is often addressed via standardised life cycle assessment (LCA), which is a commonly applied method for assessing life cycle embodied and operational environmental impacts (CEN 2012b). The LCA of buildings exists in several voluntary green building certification schemes, and recently mandatory life cycle-based climate declarations, have also become part of building regulations in several European countries, such as France, Sweden, Denmark and Finland (OneClickLCA 2022).

As part of preparing for regulation, each country defined context-specific methods and rules for how to conduct the building LCA, based on EN 15978 (CEN 2012b). Additionally, comprehensive research activities in each country have investigated the current performance of new buildings, *i.e.* statistically derived GHGe reference values for different building types. The reference values can serve as benchmarks to show the level of reference for new-builds. They can be further used in a policy context, where negotiated limit values may be introduced in regulation to specify the minimum performance requirements (Lützkendorf & Balouktsi 2023).

The LCA-based method and rules development in the Nordic countries of Sweden, Denmark and Finland have been characterised by a high level of knowledge exchange and explicit intentions for some level of harmonisation. However, each national approach, including its methods and rules definitions, is still very context specific due to preconditions of industry practices as well as applicability (Rasmussen & Birgisdóttir 2016). For instance, the scope of life cycle stages varies, as well as the scope of inventory elements to include in the assessment (Rasmussen *et al.* 2023). One thing that the Nordic approaches have in common, though, is the development focus on new buildings: each method is developed with regulation for new buildings in mind, and the complementary reference values are likewise associated with the performances of new-build. A key concern in the construction of new buildings is the high level of resources used and embodied GHGe emitted 'upfront', *i.e.* from production of materials, their transport and installation into the building (Birgisdottir *et al.* 2017; Röck *et al.* 2019). These upfront emissions are a direct threat to the immediate cuts in GHGe needed to keep the global temperature around 1.5°C (IPCC 2023). Strategies for reducing GHGe from the building and construction activities thus have the upfront emissions as well as the whole life cycle perspective to take into account.

Recently, the focus is starting to change from new-build to renovation of existing constructions. Agendas of circular economy and net-zero GHGe are widely being set as a basis for European Union policy initiatives for more sustainable construction (Kylili & Fokaides 2017; Sala *et al.* 2021), pushing towards increased importance of building renovation as a key strategy to reduce impacts rapidly. Examples of this are the Renovation Wave initiatives and the revised Energy Performance in Buildings Directive where LCA-based whole-life carbon assessments are introduced alongside the establishment of Renovation Passports for existing buildings (European Commission 2020, 2021).

A growing number of scientific publications present LCA-based assessments of building renovations (Fahlstedt *et al.* 2022). Typically, the studies assess renovation cases in their own right (Galimshina *et al.* 2022; Ghose *et al.* 2017; Shirazi & Ashuri 2020) or compared with reference numbers from new-build (Marique & Rossi 2018; Schwartz *et al.* 2018). Key methodological issues have also been highlighted in the existing literature, such as those concerning the allocation of impacts between systems (Hasik *et al.* 2019; Obrecht *et al.* 2021; Zimmermann *et al.* 2022), or the environmental payback times of material investments (Asdrubali *et al.* 2019; Brown *et al.* 2014; Passer *et al.* 2016; Valančius *et al.* 2018). However, it has not been investigated in detail to what degree the current national LCA-based approaches developed for new-build are fit for use in GHGe assessments of renovations. There may be challenges in the methods and rules definitions that are specifically challenging when assessing renovation. With the increased focus on integrating LCA requirements in building legislation, assessments of renovation projects are still an evolving field of practice and policy, and the limits and incentives in renovation LCA for policymaking are not apparent in the current literature.

The aim of this paper is to analyse how the existing Swedish, Danish and Finnish approaches to LCA-based GHGe assessments perform in renovation projects, to investigate their influence on renovation versus demolition and new-build, and to reflect upon methodological challenges specific to the renovation context.

The scope of LCA approaches for analysis are set to the Nordic countries of Denmark, Sweden and Finland as an example of a region where methodological coordination and knowledge-sharing have been an explicit focus of the policymaking. The scope of the three countries enables a geographically equivalent context, since climatic conditions and building practice are similar in Denmark and in the southern areas of Sweden and Finland. Thus, in this study a generic refurbishment case for energy demand reductions in a multi-family building is assessed with the three different LCA-based approaches used in the three regulations, respectively. The results are analysed and discussed to answer the following research questions:

- How does the renovation case position itself against demolition and new-build in the three approaches?
- Which method-related aspects concerning upfront and future GHGe are important to highlight for future development of methods?

2. METHODS

LCA-based GHGe assessment is performed on a building renovation case. The assessment is carried out by using the Swedish, Danish and Finnish LCA approaches, all of which are still under development. These approaches are used to investigate how the case positions itself against demolition and new-build. The performance level of the new-build is statistically derived reference values from the respective countries.

The study compares the steering effects and incentives for renovation promoted by the different approaches. The national LCA-based approaches have inherent differences, and it falls outside the scope of this study to discuss the method-related differences in absolute values between the three different approaches. However, key methodological aspects of the approaches will be discussed and considered for future development.

2.1 ASSESSMENT METHOD ACCORDING TO THE NATIONAL APPROACHES

The European standard EN 15978 (CEN 2012b) is followed for assessing GHGe due to buildings' life cycle. The standard focuses on the impact category global warming potential (GWP), also referred to as climate impact. This impact category has a large political focus and is the most used in legislation (Butera *et al.* 2021). The national approaches used in this paper include the following:

- The 'Swedish approach' is the method for GHGe assessment for the climate declaration for new-build, in effect from 1 January 2022 (The Swedish Parliament 2021). There are currently no requirements for renovation in legislation, but it was chosen to use the same limited scope (modules A1–A5) and method to define the Swedish approach in this paper.
- The 'Danish approach' follows the method from the voluntary sustainability class for new-build and renovation in Denmark (Danish Transport Construction and Housing Authority 2020).
- The 'Finnish approach' is the proposed method (Ministry of the Environment 2022) for a mandatory climate declaration for new-build or deep renovation projects, which will be required from 2025 onwards.

Note that the national approaches are all subject to ongoing development and changes, in terms of both methodological configurations and background data for assessments. The investigation for this paper thus reflects the state of play for the approaches in use at the beginning of 2023. The approaches represent three levels of completeness in terms of both life cycles stages and the type of building components (existing and new materials) included in the assessment. This is illustrated in Table 1, which shows the life cycle stages included in the three national approaches. Table 2 describes the assessment methods for each approach based on the standard EN 15978 (CEN 2012b). It describes the methodological choices and calculation rules that are specific to the three approaches.

2.2 DESCRIPTION OF THE RENOVATION CASE

The case consists of a group of multifamily building blocks with a concrete structure from 1972. Details on the building properties can be found in Table 3. The buildings were renovated for energy efficiency purposes, and balconies expanded. The renovation project also included the removal of asbestos from the parapets. All renovation actions are listed in Table 4. All quantities from new materials can be found in the supplemental data online. This case is a real renovation project of Danish building blocks and was selected for the comparative analysis because it is considered representative for all three countries (Denmark, Sweden, Finland), as a generic multifamily building from the 1970s using prefabricated concrete elements. Furthermore, the renovation actions are typical of the construction type and commonly undertaken in all compared countries. The energy use of the building is based on the Danish energy demand calculation (Danish Building Regulations 2023) for the Danish climate. The energy use before and after renovation is listed in Table 5.

2.3 ASSESSMENT OF THE RENOVATION CASE:

As previously explained, the national methods presented in Table 2 were followed to perform the GHGe assessments. However, the details of the case described above demand modelling adjustments of the national approaches. Further specifications on the modeling are presented in Table 6, and quantities from new and existing materials are in the supplemental data online.

2.4 COMPARISON WITH DEMOLITION AND NEW-BUILD

To understand how the renovation case compares with demolition and new-build, a comparable 'demolition and new-build' scenario is developed. This is done by using statistically derived reference values for new-build based on representative case samples in each country under study (Table 7). Reference values refer to values aiming at neutrally representing current new-build climate performance in the study countries (Malmqvist *et al.* 2023). To be consistent with each country's approach, these reference values were retrieved from published reports supervised by official institutions, in which the choice of statistical values considered to be representative are in line with the ISO (2021) standard. However, while the Finnish report (Granlund Oy 2021) communicates reference values using mean values, the Danish report (Zimmermann *et al.* 2021) communicates results with median values. The Swedish report communicates both mean and median values, which are almost identical (Malmqvist *et al.* 2023).

The reference values also differ in the reference units in which they are communicated (Table 7). The Swedish approach uses gross floor area, the Finnish uses heated floor area, and the Danish uses a weighted combination of both. Furthermore, Denmark's and Finland's reference units are divided by the reference study period (RSP).

The method and unit differences in the national reference values means they are not easily compared. However, the purpose of this study is not to compare reference values, but to understand their influence on renovation projects within their national contexts. Therefore, the reference values are adjusted to the case building: the reference values are multiplied by the corresponding floor areas of the case and the RSP for the Danish and Finnish values. These case-specific reference values are shown in Table 7.

Table 1: Life cycle modules included in the national approaches in Sweden (SE), Denmark (DK), and Finland (FI).

Note: Existing materials area shown as 'disposed' and 'remaining' depending on if they are disposed as part of upfront emissions, or remain in the building after the renovation. Modules $C3_{di}$, $C4_{di}$ and D_{di} are used in the Danish approach to separate end-of-life emissions from disposed materials. In the Finnish approach, these are included in A5 and D.

New = new materials added in the renovation; Disposed = materials removed during the renovation process; Remaining = materials kept in the building after renovation; Op. energy = operational energy use of the building.

		WASTE PROCESS	DIS-POSAL	BENEFITS/ LOADS	PRODUCT STAGE	TRANS-PORT	CONSTRUC-TION	USE	MAINTEN-ANCE	RE-PAIR	REPLACE-MENT	REFUR-BISHMENT	OP EN-ERGY USE	OP WATER USE	DECON-STRUCTION	TRANS-PORT	WASTE PROCESS	DIS-POSAL	BENEFITS/ LOADS
		$C3_{di}$	$C4_{di}$	D_{di}	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
SE	New																		
	Disposed																		
	Remaining																		
	Op. energy																		
DK	New																		
	Disposed																		
	Remaining																		
	Op. energy																		
FI	New																		
	Disposed																		
	Remaining																		
	Op. energy																		

Table 2: Assessment methods for renovation-life cycle assessment (LCA) using Swedish, Danish, and Finnish approaches.

Note: EoL = end-of-life; EPDs = environmental product declarations; LCIA = life cycle impact assessment; RSP = reference study period; SL = service lives.

	SWEDISH APPROACH	DANISH APPROACH	FINNISH APPROACH
RSP	Only includes upfront emissions. No need of the RSP	50 years	50 years
Transportation in construction (A4) for new materials	Use of standard values developed for the Swedish context connected to each product type to enhance representativeness (The Swedish National Board of Housing and Planning 2023)	Not part of the assessment for the building permit	Use of standard values depending on the transportation type developed using Finnish statistics and previous studies (Finnish Environment Institute 2023)
Construction (A5)	Consideration of the waste on site of the new materials. No packages. Only consideration of the production and transport, not the EoL processes. Available in the database (The Swedish National Board of Housing and Planning 2023)	Not part of the assessment at the building permit	Includes waste and energy use on the building site in accordance with EN 15804 (Finnish Environment Institute 2023)
Replacement scenario (B4) for new materials	Not included	Considered based on the SL of building elements from the build report (Haugbølle *et al.* 2021)	Considered based on the SL available in the database (Finnish Environment Institute 2023)
Replacement scenario (B4) for remaining materials	Not included	Based on the remaining SL and RSP	Based on the RSP
Energy use in operation (B6)	Not included	**Energy use based on Energy Performance Certificates**	
		GHGe intensity/kWh or /MJ from COWI (2020). Standard values, which include the energy decarbonisation scenario 2020–40, represent national district heating and electricity	GHGe intensity/kWh or /MJ from the database. Standard values, which include the energy decarbonisation scenario 2020–2120, represent national district heating, district cooling and electricity (Finnish Environment Institute 2023)
Deconstruction and demolition (C1)	Not included	Not included	Typical values based on Finnish previous studies. (Finnish Environment Institute 2023)
Transportation in EoL (C2) for new and remaining materials	Not included	Not included	The final result is calculated in terms of kg CO_2e/m^2 based on the case-specific volumes of demolition waste and with the help of CO2DATA for transportation (Finnish Environment Institute 2023)
Benefits and loads beyond the system boundaries (D) for new and remaining materials	Not included	Available in the database. Include benefits of reuse, recycling and energy recovery; and surplus renewable energy	Available in the database. Include benefits of reuse, recycling and energy recovery; long-term carbon storages; carbonation and surplus renewable energy
Background database (GHGe intensity of construction products)	Boverket database (use of conservative data). The value is based on the weighted average from existing EPDs (The Swedish National Board of Housing and Planning 2023). It is also possible to use EPDs for specific products	GEN_DK: an extract of generic data from the Ökobau 2021 LCIA database combined with Danish average EPDs from industry associations (Danish Housing and Planning Authority 2023). It is also possible to use EPDs for specific products	National GHGe database for construction (use of conservative data). The value is based on the weighted average from existing EPDs (Finnish Environment Institute 2023). It is also possible to use EPDs for specific products

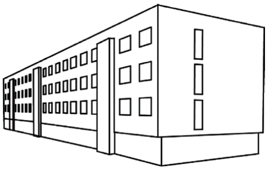
RENDERING OF THE BUILDING AFTER RENOVATION	BUILDING PROPERTIES		COMMENTS
	Gross floor area	41,255 m^2	Gross area is measured from the outside of the external walls and includes the basement
	Heated floor area	32,234 m^2	Heated floor is measured from the outside of the external walls
	Floors	4 (including ground floor)	Ground floor is mostly unheated, floors 1–3 are heated
	Basement	1,414 m^2	
	Heating system	District heating	

Table 3: Properties of the renovation case building.

Table 4: Description of the renovation actions.

		DESCRIPTION	NEW MATERIALS ADDED IN THE RENOVATION
Roof	Roofing	New roofing on staircase towers and balcony towers	Roofing felt (two layers)
	Attic	Insulation in attic	300 mm mineral wool
	Eaves	Replacement of eaves	Construction wood Plywood
Balconies	Balconies	Expansion of balconies and enclosing them in glass (not heated).	Fibre-reinforced concrete and plaster for the balcony extension Light walls with zinc, steel, fibre cement board and paint Mineral wool under the lower balconies Safety glass for closing off the balcony
External walls	Staircase towers	Replacing outer walls (light walls)	Steel Fibre cement board 195 mm mineral wool Vapour barrier 50 mm mineral wool Gypsum (three layers) Paint
	External walls	Insulation of the external walls	100–160 mm mineral wool (for the facade) Plaster
Slabs	Flooring	New floors in the apartments and weather porch	Wooden floors with mineral wool Slate flooring and mortar
	Ceilings	Insulation in the ceiling of the unheated area on the ground floor. New ceilings in the staircase	Mineral wool Steel Fibre cement boards Paint Mineral wool acoustic ceilings
Windows	Windows and doors	Most windows and external doors are replaced	Thermal windows (three layers) Wood/aluminium window frame Slate window ledges Aluminium curtain wall for the staircase tower

Table 5: Calculated energy demand from heating, ventilation and hot water of the building before and after renovation per heated floor area.

	BEFORE (kWh/m^2/year)	AFTER (kWh/m^2/year)
Heating (district heating)	135.8	86.4
Electricity use	0.7	0.7

	SWEDISH APPROACH	DANISH APPROACH	FINNISH APPROACH
Product stage (A1–A3) for new materials	Inventory data are based on accessible data for the case. They include the building envelope, load-bearing structural parts, interior walls and internal surface layers		
Transportation in construction (A4 and C1) for new materials	–	Not included	Distance and transportation type based on background data (Häkkinen 2021)
Construction (A5)	Use of waste factor for each building product from the national database (The Swedish National Board of Housing and Planning 2023)	Not included	Construction site emissions based on the renovation case in the background data (Finnish Environment Institute 2021)
Replacement scenario (B4) for the remaining materials	Not included	If the material provides a structural function, then service life = reference study period, otherwise same service life as the new material	
Energy use in operation (B6)	Not included	Energy use based on the energy demand calculation for the Danish context (Danish Building Regulations 2023)	
Deconstruction and demolition (C1)	Not included	Not included	Standard value for the demolition of residential buildings from the national database is used
Waste processing and disposal (C3–C4) for new and remaining materials	Not included	Does not include end of life of the existing building services, as these inventory data were not available	
Benefits and loads beyond the system boundaries (D) for new and remaining materials	Not included	–	Include the recycling of steel and long-term biogenic or technical carbon storage

Table 6: Detailing of the modeling used in the GHGe assessment of the renovation case.

Note: For quantities of materials, see the supplemental data online.

Finally, the alternative scenario to renovation not only includes building new but also the demolition of the existing building. Therefore, the GHGe from demolition of the case building calculated following the national approaches are added to the reference value for Finland and Denmark (Table 7). It is not included for Swedish values, as the system boundaries in the Swedish approach do not include existing materials. The Danish and Finnish renovation approaches already include the end-of-life (EoL) of all the building elements of the already existing building as part of the system boundaries of the renovation case (spread across the life cycle) (Table 4). Consequently, it is necessary to include demolition of the existing building in the 'demolition and new-build' scenario to ensure comparability.

3. RESULTS

Results show how the renovation case performs compared with the reference GHGe values for new-build, and investigates differences related to the timing of emissions, and the inclusion of existing materials. These are key aspects where the results differ between demolition and new-build and renovation and are therefore important for the continued development of method and regulation.

3.1 RENOVATION VERSUS DEMOLITION AND NEW-BUILD

Following the objective of this study, this first result section introduces the results of the renovation case compared with the 'demolition and new-build' scenario defined in subsection 2.4.

All national approaches perform better for the renovation case than for new-build and demolition. However, the approaches give significantly different results for the renovation case, as well as their result compared with the reference value. This can be seen in Figure 1, which shows how the renovation case positions itself against demolition and new-build for the three national approaches.

	VALUE TYPE	STAGES	ORIGINAL REFERENCE VALUE	CASE-SPECIFIC REFERENCE VALUE (10^3 ton CO_2-eq)	REFERENCES
			(kg CO_2-eq/m²)[a]		
Sweden	Mean (new-build)	A1–A5	368	15.2	Malmqvist *et al.* (2023)
			(kg CO_2-eq/m²/year)[b]		
	Demolition of existing building	*C3, C4*	–	*2.4*	*From case*
Denmark	Median (new-build)	A1–A3, B4, B6, C3–C4	9.5	18.4	Zimmermann *et al.* (2021)
	Median for modules (new-build)	A1–A3	5.4	11.2	Nielsen *et al.* (2022)
		B4	0.9	1.9	
		B6	2.6	4.2	
		C3, C4	1.0	2.1	
			(kg CO_2-eq/m²/year)[c]		
	Demolition of existing building	*C1–C4*	–	*4.1*	*From case*
Finland	Mean (new-build)	A1–A5, B4, B6, C1-C4	16	25.8	Granlund Oy (2021)
	Mean for modules (new-build)	A1–A5	7	11.3	
		B4, B6	5	8.1	
		C1–C4	4	6.4	

Table 7: Original and case specific reference values for new-build and demolition of existing building for the different life cycle stages.

Note: [a] Reference unit based on gross floor area.

[b] Reference unit based on gross floor area for material impact and heated floor area for operational energy use. Based on a 50-year reference service period.

[c] Reference unit based on heated floor area and the 50-year reference study period.

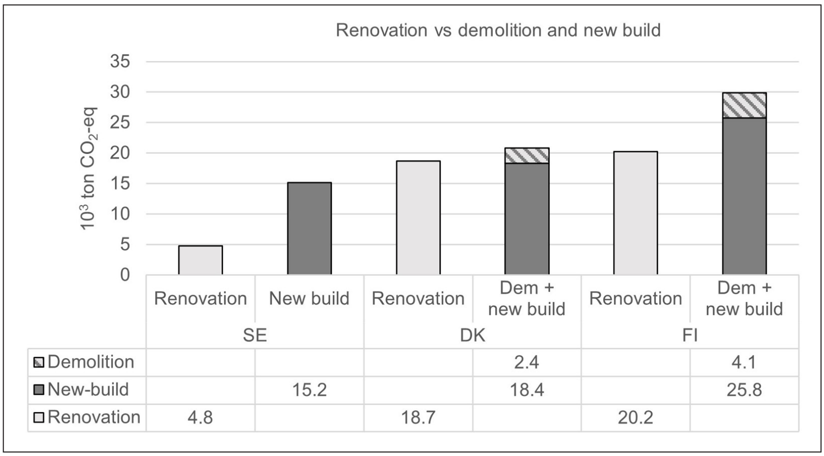


Figure 1: Results from the renovation case compared with demolition ('dem') and new-build reference values over 50 years.

The Swedish approach on the renovation case has the lowest GHGe of the three national approaches. The Swedish approach also gives the best relative performance of the renovation case compared with the reference values for new-build, with 68% lower GHGe from the renovation. The Finnish approach has the overall highest GHGe, and the renovation case results are 32% below the reference values for new-build and demolition. The Danish approach gives slightly lower GHGe than the Finnish approach, but the renovation case results are just 10% below the reference value for new-build and demolition. For the Danish case, the reference values for new-build alone (without demolition) is lower than the GHGe from the renovation case. To understand how the methods affect the differences in the results, the next section will consider the GHGe calculations over a time scale.

3.2 TIMING OF EMISSIONS

When considering the temporal perspective of GHGe, it becomes easier to understand the differences in the results of the national approaches and their performance compared with new-build. Figure 2a shows the GHGe over time for the renovation case and the reference value for each approach. Figure 2b shows the contribution from building products (embodied impacts) and operational energy use (operational impacts) from upfront and future GHGe compared with the reference value for each approach.

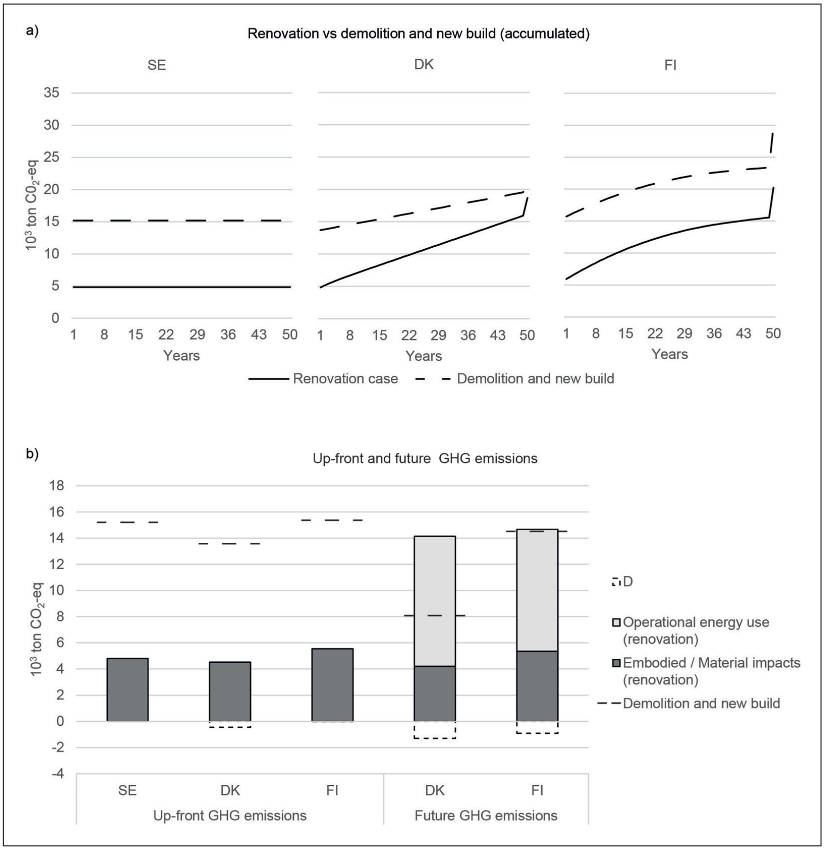


Figure 2: Temporal differences between renovation and new-build for embodied and operational impacts.

Note: (a) Greenhouse gas emissions (GHGe) from the case accumulated over time compared with demolition and new-build; and (b) what contributes to the impacts over time. Loads and benefits beyond the system boundaries (stage D) are shown as negative at the time they occur.

Figure 2 shows that for all countries, the renovation case has significantly smaller GHGe the first year (upfront emissions) in comparison with the reference value. Upfront emissions do not vary significantly across the national approaches. The reason upfront emissions are lower for renovation is due to less disposal of existing building components and hence less needed production of new materials. The Danish and Finnish approaches include the use stage (years 1–49). Here, the renovation case performs worse than the scenario based on reference values. Though the renovation case includes many energy-retrofitting actions, Figure 2b shows that the GHGe from energy for this case is still higher for the renovation case than for new-build, especially for the

Danish approach. Year 50 in Figure 2a shows that EoL emissions for the renovation case are similar to reference values for new-build for both Denmark and Finland. This could be expected as both the reference values and the renovation case consider the EoL of the whole building following the assessment method for the national approaches. Figure 2b shows that the main contributor to future emissions (years 1–50) for the renovation case is the operational energy use of the building. Thus, the contribution of future emissions—in particular from the operational energy use—is the reason the performance of the renovation case performs worse for the Danish and Finnish approaches compared with the Swedish approach in Figure 1.

3.3 UPFRONT EMISSIONS

Though the results appear similar for upfront emissions across the national approaches in Figure 2, the results detailed according to the contribution of life cycle stages of different material types (new versus disposed) of upfront emissions are different. Figure 3 shows the upfront emissions of the renovation case for the three approaches. The upfront emissions consist of emissions from the 'new materials' installed in the building, and the emissions due to the EoL processes of disposed materials. These are considered in modules C3 and C4 in the Danish approach and in A5 in the Finnish approach (Figure 3) as long as the materials have the status of 'waste' (CEN 2019).

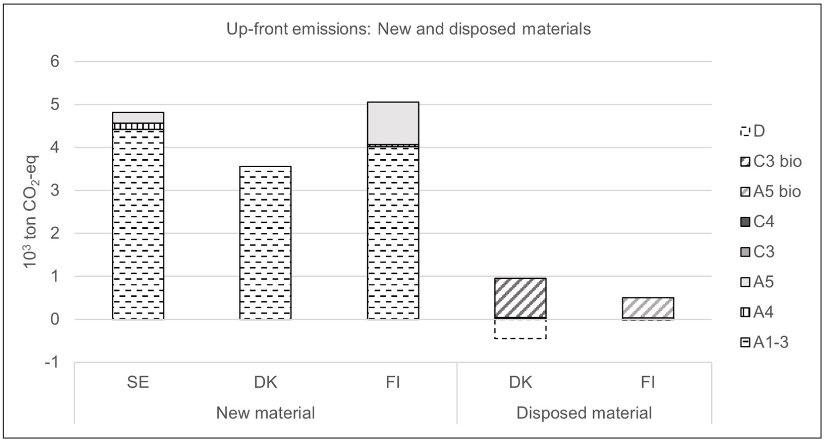


Figure 3: Upfront embodied emissions from new and disposed materials using Swedish (SE), Danish (DK) and Finnish (FI) calculation approaches.

Note: A large part of the emissions are from biogenic material ('C3 bio' and 'A5 bio'), where end-of-life (EoL) processes only include the emissions of biogenic CO_2.

Results show that the GHGe due to the production of new materials (A1–A3) are significantly lower for the Danish and Finnish approach than for the Swedish approach. This is mainly due to the differences in the databases of handling the biogenic materials. Following EN15804+A1 and A2, respectively, the Danish and Finnish databases consider the removal of CO_2 into biomass as negative emissions during the product stage (stage A) and as positive emissions during EoL processes (CEN 2019). This results in zero net CO_2 emissions across the stages. The Swedish database does not include biogenic carbon since it only considers module A, resulting in higher emissions from new materials in the product stage. However, many of the biogenic materials are replaced; the upfront biogenic carbon is therefore close to neutral, leading to similar total values for the upfront emissions between the three approaches. Indeed, the EoL processes of the disposed materials contribute 21% of the upfront emissions for the Danish approach and 9% for the Finnish approach. Of these impacts, 95% and 94% come from materials with the release of biogenic carbon such as wood flooring or window frames for Denmark and Finland, respectively. For the assessment of disposed materials in renovation calculations, only EoL stages are included. Therefore, only the release of biogenic carbon is considered.

Figure 3 also displays module D, which captures the potential loads and benefits deriving from the recycling, energy recovery or reuse of the disposed products outside the system boundaries—

once the product is not considered as 'waste' anymore. Module D is not aggregated with other modules in the approaches studied and in current standards (CEN 2019). The assessments of module D vary significantly between the Danish and Finnish approaches: in the Danish approach it would correspond to 9% of upfront emission, if included, and less than 0% for the Finnish. This is because at the time of this study, the Finnish database only included benefits from the recycling of metals which are part of the Finnish 'carbon handprint' approach (Häkkinen *et al.* 2021). The Danish approach follows EN15804+A1 (CEN 2012a), thus including other recycling potential as well as energy recovery, which results in larger benefits.

4. DISCUSSION

The discussion addresses the potential influence that national approaches have in terms of the promotion of renovation or new-build, as well as method considerations for adaptations of the approaches to renovation projects.

4.1 RENOVATION VERSUS NEW-BUILD

The results for the case building showed that the Swedish approach provides the largest incentive to renovate the case building rather than building new. This is followed by the Finnish and then the Danish approach, which is just 9% lower than the reference value.

The significantly better performance of the renovation case in the Swedish approach is mainly due to the system boundaries, which only include upfront emissions. The results illustrate that this difference in system boundaries between the three approaches can lead to different incentives in practice. The Danish and Finnish inclusions of operational GHGe incentivise an increased focus on reducing these in a renovation case. This could encourage deeper renovations in order to reduce the operational energy use to match the level of new-build. On the other hand, the Swedish approach encourages low upfront material use independently of the extent and goal of the renovations. Another, more practical aspect is the benefit of a simpler calculation approach for the practitioner. The Swedish approach has the advantage of not accounting for any existing materials, as only new materials are included in the assessment, hence greatly reducing complexity.

4.2 REFERENCE VALUES USED FOR RENOVATION CASES

4.2.1 Demolition

For this study, the renovation case was compared with a scenario where a new building is constructed and the existing building is demolished. Reference values from previous studies were used for GHGe from new construction Danish and Finnish values, the value included GHGe from the demolition of the existing building, hence the associated disposal of materials. The inclusion of the latter proved to be important for the Danish comparison in this case (Figure 1), thus making the difference between whether renovation or new construction provided the lowest results of GHGe. This highlights the importance of system boundaries to ensure comparability between renovation and new-build. For instance, it is needed to include demolition in the reference value, when using approaches such as the Danish and the Finnish, where emissions from existing materials are included in the system boundaries of renovation.

This is specifically important at a time when limit values for new-build are also often applied to larger renovation projects (Lund *et al.* 2022). Again, the inclusion of demolition also complicates and adds to the workload. These calculations must be based on the specific case which demands a full inventory of the existing building or generic values need to be created.

4.2.2 Temporal differences

The results showed clear differences in the timing of emissions between the renovation case and the new-build scenario. The timing of emissions is important due to the need for immediate reduction of GHGe to keep the global temperature increase at 1.5°C. The new-build scenario has most GHGe upfront for all three national approaches. In contrast, most GHGe from the renovation case takes place during the modelled use and EoL stages as illustrated by the Danish and Finnish approaches. When all results are aggregated over the included life cycle modules, only the Swedish approach specifically incentivises the reduction of upfront emissions.

A possible way of incorporating the temporal perspective, while still including a life cycle perspective, is to report separately life cycle modules or divided into upfront and future emissions. This disaggregated reporting is illustrated in Figure 2b, and also demanded in the current Finnish and French regulations (Ministry of the Environment 2022; Ministère de la Transition écologique 2020). This can help give an incentive to reduce upfront emissions as a separate declaration.

4.3 EXISTING MATERIALS

The temporal perspective is also relevant when including existing materials of the renovation. The Danish and Finnish approaches include GHGe from the EoL processes of the disposed of materials during the renovation process, as well as the replacement and EoL processes of the 'remaining' materials kept in the renovated building. Including these existing materials can be relevant in providing incentives for reuse and recycling of existing materials:

- *Incentive for reuse on site*

  Onsite reuse of materials postpones upfront EoL emissions to future EoL emissions at the end of the buildings' service life This is only visible if a temporal perspective is considered. The results (Figure 2b) show that the inclusion of disposed materials' EoL has a considerable impact on upfront embodied emissions. However, the results also show that these emissions were mainly from bio-based materials. Therefore, the inclusion of existing materials will mainly incentivise the reuse of biogenic materials, which is further discussed below.

- *Incentive for reuse in other projects*

  Benefits from the reuse of disposed building materials are calculated outside of the system boundaries—in module D. Hence, only the emissions due to EoL recycling processes are included, but not the potential emission saving from recycling or reusing it in another system. However, these specific benefits happen around the time of the renovation activities, and thus could be considered in the upfront emissions. Development in data availability is, however, also needed if module D is intended to be included in the declaration to give incentive to encourage better reuse and recycling. Reuse in other projects can also simply be considered by not including any EoL processes for these products as proposed in the Finnish method (Ministry of the Environment 2022). Rewarding reuse and recycling should also be allowed only if such practices are truly implemented.

On a practical perspective, it should be considered if these incentives make up for the extra work that is also associated with mapping all the existing materials for the assessment. It is also relevant to consider whether the renovation project is responsible for the burden from the EoL of the existing materials that they have had no influence on choosing, as suggested by Hasik *et al.* (2019).

4.4 BIOGENIC MATERIALS

The inclusion of existing materials contributes to methodological challenges for biogenic materials. The results in Figure 3 show clear disadvantages in disposing biogenic materials compared with other materials. This is due to the methods used in the Danish and Finnish databases, which only consider the emissions of CO_2 from the biomass (since the uptake of biogenic CO_2 has happened at biomass growth, before the renovation and thus part of the preceding life cycle of the building). Though the same GHGe will apply to a possible demolition, the communication of results will be difficult, especially when compared with other renovation projects or new-build (without demolition). Here, buildings with a lot of biogenic material will have a disadvantage, and could be considered worse than new construction.

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4.5 LIMITATIONS OF STUDY

The results in this study represent a snapshot of how methods are used at the time of writing this paper, but the methods are developing quickly, including changes in the databases used, and the definition of reference values. Thus, specific numbers reported for reference values and results in this study only have limited relevance in a long-term perspective. However, focus for the study has been the analyses of methodological challenges, which have a more persistent and general relevance.

Further, this study is based on a single renovation project to highlight the immediate challenges observed from the national approaches and the associated reference values. However, renovation projects vary significantly, also in the scale and purpose of the renovation, and may involve more technical installations, which was not a part of this assessment. Testing methods on other types of renovation cases may lead to additional methodological issues, and could thus be a topic for future research efforts.

5. CONCLUSIONS

This study explores how Danish, Finnish, and Swedish life cycle assessment (LCA)-based greenhouse gas emissions (GHGe) assessments perform for building renovations compared with new-build, and what steering effects they have. The study further investigates which method-related aspects are important to highlight for performance evaluation of renovations. This has been investigated by using a generic real case study to illustrate the three national approaches which have been developed in a similar geographical context and with a common focus on methodological coordination and knowledge-sharing.

Results show that the system boundaries (inclusion of the existing building materials in the assessment) as well as the timing of GHGe are aspects of specific relevance when comparing renovation with new-build. All approaches display lower upfront emissions for the renovation project compared with new-build. However, the inclusion of the future emissions in the Danish and Finnish approaches provided less incentive for renovation against new-build, compared with the Swedish approach, which only includes upfront emissions. This was particularly due to the difference in operational energy use between the renovation case and new construction. Furthermore, the inclusion of storage and release of biogenic carbon as well as disposed material leads to different results for the upfront emissions in the three approaches.

Accounting for existing material in climate declarations for the renovated building can incentivise reuse under the condition that upfront emissions are reported separately from future emissions. The inclusion of biogenic carbon, as advocated by the EN 15804 standard, can promote reuse, but also bears the risk of burdening renovation projects that have a high content of biogenic materials.

On a practical perspective, including the assessment of existing materials leads to significant additional workload in establishing the inventory. The tested national approaches do not currently provide an incentive for upfront reuse of disposed materials in other projects, since the potential benefits are considered to be outside the system boundaries (in 'module D'). However, the study also conveys that even if they are considered, data are currently lacking for end-of-life (EoL) and potential benefits from reusing materials.

The study demonstrates the relevance in considering the temporal perspective when comparing renovation with demolition and new-build. A suggested way of incorporating this temporal perspective is to ensure that GHGe are reported for individual life cycle modules in climate declaration regulations, or between upfront and future emissions. Such an approach is also relevant for potential development of limit values. Thus, the results can communicate on the potential temporal 'gains' from renovation while promoting the reuse of existing materials onsite. Development in methods towards more dynamic future scenarios could also highlight the importance of upfront emissions.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

Data are available for the materials and quantities used for new and existing materials for the renovation case study.

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SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: https://doi.org/10.5334/bc.325.s1.

REFERENCES

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., & **Guattari, C.** (2019). Energy and environmental payback times for an NZEB retrofit. *Building and Environment*, 147(October), 461–472. DOI: https://doi.org/10.1016/j.buildenv.2018.10.047

Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Lützkendorf, T., & **Malmqvist, T.** (2017). IEA EBC Annex 57: Evaluation of embodied energy and CO_2eq for building construction. *Energy and Buildings*, 154, 72–80. DOI: https://doi.org/10.1016/j.enbuild.2017.08.030

Brown, N. W. O., Olsson, S., & **Malmqvist, T.** (2014). Embodied greenhouse gas emissions from refurbishment of residential building stock to achieve a 50% operational energy reduction. *Building and Environment*, 79, 46–56. DOI: https://doi.org/10.1016/j.buildenv.2014.04.018

Butera, S., Karl, A. A., Astrup, T. F., Collin, C., Rasmussen, N. L., & **Sørensen, L. H.** (2021). *Project on LCA and socioeconomics Task 2—Analysis of other countries' approach to building LCA*. https://www.lifecyclecenter.se/wp-content/uploads/Analysis-of-other-countries-approach-to-building-LCA.pdf

CEN. (2012a). *EN 15804+A1: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products*. https://webshop.ds.dk/en/standard/M254454/ds-en-15804-2012

CEN. (2012b). *EN 15978: Sustainability of construction works—Assessment of environmental performance of buildings—Calculation method*. https://www.en-standard.eu/din-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

CEN. (2019). *EN 15804:2012+a2:2019: Sustainability of construction works—Environmental product declarations—Core rules for the product category of construction products*. https://www.en-standard.eu/bs-en-15804-2012-a2-2019-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/

COWI. (2020). *Opdaterede emissionsfaktorer for el og fjernvarme*. https://bpst.dk/da/Byggeri/Lister/Publikationsliste?theme=Indeklima

Danish Building Regulations. (2023). *Danish Building Regulations, Pub. L. No. §298*. https://bygningsreglementet.dk/Tekniske-bestemmelser/11/Krav

Danish Housing and Planning Authority. (2023). *Generic data for building regulation*. https://bygningsreglementet.dk/Bilag/B2/Bilag_2/Tabel_7#787e83a6-b7d9-4a83-a4be-37574156daef

Danish Transport Construction and Housing Authority. (2020). *Voluntary sustainability class*. https://baeredygtighedsklasse.dk/

European Commission. (2020). Renovation Wave for Europe—Greening our buildings, creating jobs, improving lives. *Official Journal of the European Union*, 26. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662

European Commission. (2021). Proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast). *Official Journal of the European Union*, 0426, 10–27. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0802&qid=1641802763889

Fahlstedt, O., Temeljotov-Salaj, A., Lohne, J., & **Bohne, R. A.** (2022). Holistic assessment of carbon abatement strategies in building refurbishment literature—A scoping review. *Renewable and Sustainable Energy Reviews*, 167(June), 112636. DOI: https://doi.org/10.1016/j.rser.2022.112636

Finnish Environment Institute. (2021). *Report—Process—Construction site (A5)*. https://co2data.fi/rakentaminen/reports/Process-construction-3.pdf

Finnish Environment Institute. (2023). *Emissions database for construction*. www.CO2data.fi

Galimshina, A., Moustapha, M., Hollberg, A., Padey, P., Lasvaux, S., Sudret, B., & **Habert, G.** (2022). Bio-based materials as a robust solution for building renovation: A case study. *Applied Energy*, *316*(March). DOI: https://doi.org/10.1016/j.apenergy.2022.119102

Ghose, A., McLaren, S. J., Dowdell, D., & **Phipps, R.** (2017). Environmental assessment of deep energy refurbishment for energy efficiency-case study of an office building in New Zealand. *Building and Environment*, 117, 274–287. DOI: https://doi.org/10.1016/j.buildenv.2017.03.012

Giesekam, J., Tingley, D. D., & **Cotton, I.** (2018). Aligning carbon targets for construction with (inter) national climate change mitigation commitments. *Energy and Buildings*, 165, 106–117. DOI: https://doi.org/10.1016/j.enbuild.2018.01.023

Granlund Oy. (2021). *Rakennuksen Vähähiilisyyden*. https://www.granlund.fi/wp-content/uploads/2022/02/Rakennuksen-vahahiilisyyden-arviointimenetelma-2021_menetelmatestausraportti_Granlund.pdf

Häkkinen, T. (2021). *Transportation of building products (A4)—Background data*. https://co2data.fi/rakentaminen/reports/Process-transportation-of-building-materials.pdf

Häkkinen, T., Nibel, S., & **Birgisdottir, H.** (2021). *Definition and methods for the carbon handprint of buildings*. https://ym.fi/documents/1410903/40549091/Raportti+-+Definition+and+methods+for+the+carbon+handprint+of+buildings.pdf

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B., & **Bilec, M. M.** (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Building and Environment*, *161*(May), 106218. DOI: https://doi.org/10.1016/j.buildenv.2019.106218

Haugbølle, K., Mahdi, V., Morelli, M., & **Wahedi, H.** (2021). *BUILD Levetidstabel*. https://build.dk/Pages/BUILD-levetidstabel.aspx

IPCC. (fortcoming 2023). Summary for policymakers. In H. Lee & J. Romero (Eds.), *Climate change 2023: Synthesis report. A report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (IPCC). https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

ISO. (2021). *ISO 21678:2020: Sustainability in buildings and civil engineering works—Indicators and benchmarks—Principles, requirements and guidelines*. https://www.iso.org/standard/71344.html

Kylili, A., & **Fokaides, P. A.** (2017). Policy trends for the sustainability assessment of construction materials: A review. *Sustainable Cities and Society*, 35, 280–288. DOI: https://doi.org/10.1016/j.scs.2017.08.013

Lund, A., Zimmermann, R., Kragh, J., Rose, J., Aggerholm, S., & **Birgusdottir, H.** (2022). *Klimapåvirkning fra renovering: Muligheder for udformning af grænseværdier til LCA for renovering.* https://vbn.aau.dk/en/publications/klimap%C3%A5virkning-fra-renovering-muligheder-for-udformning-af-gr%C3%A6ns

Lützkendorf, T., & **Balouktsi, M.** (2023). *Benchmarking and target-setting for the life cycle-based environmental performance of buildings* (Annex 72, February). International Energy Agency. https://annex72.iea-ebc.org/Data/publications/EBC_Annex_72_Benchmarking_forEnvironmental_Performance_of_Buildings_2023.pdf

Malmqvist, T., Borgström, S., Brismark, J., & **Erlandsson, M.** (2023). *Referensvärden för klimatpåverkan vid uppförande av byggnader. Version 2, 2023* (Report TRITA-ABE-RPT-233). KTH. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-324853

Marique, A. F., & **Rossi, B.** (2018). Cradle-to-grave life-cycle assessment within the built environment: Comparison between the refurbishment and the complete reconstruction of an office building in Belgium. *Journal of Environmental Management*, 224(2018), 396–405. DOI: https://doi.org/10.1016/j.jenvman.2018.02.055

Ministère de la Transition écologique. (2020). *Guide RE2020 Réglementation Environnementale* (ed. N. Cabassud). https://www.ecologie.gouv.fr/sites/default/files/guide_re2020.pdf

Ministry of the Environment. (2022). Decree of the Ministry of the Environment on the climate declaration of a building (draft for public consultation). *Indoor Climate and Ventilation of New Buildings*, September, 1–16. https://ym.fi/en/the-national-building-code-of-finland

Nielsen, L. H., Tozan, B., Birgisdöttir, H., & **Wittchen, K. B.** (2022). *DATA_BUILD*. Aalborg University, Department of the Built Environment. https://build.dk/Pages/CO_2-krav-og-saerlige-bygningsforudsaetninger.aspx

Obrecht, T. P., Jordan, S., Legat, A., Mendes Saade, M. R., & **Passer, A.** (2021). An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment. *Journal of Cleaner Production*, 327(September), 129527. DOI: https://doi.org/10.1016/j.jclepro.2021.129527

OneClickLCA. (2022). *Construction carbon regulations in Europe*. https://www.oneclicklca.com/construction-carbon-regulations-in-europe/

Passer, A., Ouellet-Plamondon, C., Kenneally, P., John, V., & **Habert, G.** (2016). The impact of future scenarios on building refurbishment strategies towards plus energy buildings. *Energy and Buildings*, 124, 153–163. DOI: https://doi.org/10.1016/j.enbuild.2016.04.008

Rasmussen, F. N., & **Birgisdóttir, H.** (2016). *Development of the LCAbyg tool: Influence of user requirements and context*. ZEBAU—Centre for Energy Architecture and the Environment. DOI: https://doi.org/10.5445/IR/1000051699

Rasmussen, F. N., Birgisdottir, H., Malmqvist, T., Kuittinen, M., & **Häkkinen, T.** (forthcoming 2023). Embodied carbon in building regulation—Development and implementation in Finland, Sweden and Denmark. In *Routledge handbook of embodied carbon in buildings*. Routledge.

Röck, M., Ruschi Mendes Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., Frischknecht, R., Habert, G., & **Lützkendorf, T.** (2019). Embodied GHG emissions of buildings—The hidden challenge for e ff ective climate change mitigation. *Applied Energy*, 258(June), 114107. DOI: https://doi.org/10.1016/j.apenergy.2019.114107

Sala, S., Amadei, A. M., Beylot, A., & **Ardente, F.** (2021). The evolution of life cycle assessment in European policies over three decades. *International Journal of Life Cycle Assessment*, 26(12), 2295–2314. DOI: https://doi.org/10.1007/s11367-021-01893-2

Schwartz, Y., Raslan, R., & **Mumovic, D.** (2018). The life cycle carbon footprint of refurbished and new buildings—A systematic review of case studies. *Renewable and Sustainable Energy Reviews*, 81(1), 231–241. DOI: https://doi.org/10.1016/j.rser.2017.07.061

Shirazi, A., & **Ashuri, B.** (2020). Embodied life cycle assessment (LCA) comparison of residential building retrofit measures in Atlanta. *Building and Environment*, 171(January), 106644. DOI: https://doi.org/10.1016/j.buildenv.2020.106644

The Swedish National Board of Housing and Planning. (2023). *Boverket*. https://www.boverket.se/sv/klimatdeklaration/gor-sa-har

The Swedish Parliament. (2021). *Act (2021:787) on Climate declaration for buildings*. https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/lag-2021787-om-klimatdeklaration-for-byggnader_sfs-2021-787

UNEP. (2020). *2020 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*. United Nations Environment Programme (UNEP). http://www.ren21.net/resources/publications/

Valančius, K., Vilutienė, T., & **Rogoža, A.** (2018). Analysis of the payback of primary energy and CO_2 emissions in relation to the increase of thermal resistance of a building. *Energy and Buildings*, 179, 39–48. DOI: https://doi.org/10.1016/j.enbuild.2018.08.037

Zimmermann, R. K., Andersen, C. M. E., Kanafani, K., & **Birgisdottir, H.** (2021). *Whole life carbon assessment of 60 buildings: Possibilities to develop benchmark values for LCA of buildings*. https://vbn.aau.dk/en/publications/whole-life-carbon-assessment-of-60-buildings-possibilities-to-dev

Zimmermann, R. K., Rasmussen, F. N., Kanafani, K., Malabi Eberhardt, L. C., & **Birgisdóttir, H.** (2022). Reviewing allocation approaches and modelling in LCA for building refurbishment. *IOP Conference Series: Earth and Environmental Science*, 1078(1). DOI: https://doi.org/10.1088/1755-1315/1078/1/012095

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Appendix C. Publication III

Publication III: **Reviewing allocation approaches and modelling in LCA for building refurbishment**. Zimmermann, R. K., Rasmussen, F. N., Kanafani, K., Eberhardt, L. C. M. & Birgisdottir, H. In: IOP Conference Series: Earth and Environmental Science, 2022, 1078

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Reviewing allocation approaches and modelling in LCA for building refurbishment

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Reviewing allocation approaches and modelling in LCA for building refurbishment

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Abstract. With a growing building stock and initiatives such as the European "renovation wave" which aims to double the annual energy renovation rates in the next ten years, environmental assessment of building refurbishment becomes still more important. Using standardized environmental assessment methods such as life cycle assessment (LCA) on renovation projects is important to keep impacts low, and avoid burden shifting. However, a specific methodological challenge in refurbishment projects is how to include the existing building materials in the assessment. The aim of this study is therefore to present and characterise different existing allocation approaches for LCA in refurbishments. Furthermore, the study highlights advantages and disadvantages of the analysed approaches from an LCA practitioner's view. A literature review was conducted to find studies that illustrate the different allocation approaches and modelling of the existing materials in refurbishment projects. The approaches characterised in the study include allocation using 50:50, avoided burden, product environmental footprint (PEF), burden-free (and semi-burden-free), residual value or depreciation, and adjusting for past production of existing materials. The implications for LCA-practitioners were evaluated based on the work burden required for application. Here, the main cons relate to the large workload connected to modelling the existing building.

Keywords: building, refurbishment, life cycle assessment, allocation, renovation

1. Introduction

Refurbishment projects play an important role in the fulfillment of climate targets. In the EU, 85-95 % of the building stock will still be standing in 2050 [1] and many of these buildings need upgrades due to e.g. bad energy performance or inefficient use. For refurbishment projects as well as new construction, it is important to consider the environmental impact of materials along with energy use to avoid shifting environmental burdens from operational energy to building materials. A method for determining the resource use and environmental impacts from refurbishment is the common and standardized method; life cycle assessment (LCA). In LCA, environmental impact potentials from both materials and operational energy use are included across the building life cycle. In this paper, we focus on impacts embodied in building materials.

A specific methodological challenge in refurbishment projects, however, is how to include the *existing* building materials in the assessment. This includes the question *if* the existing building materials should be included at all, and if so, *how much* of the existing building materials should be included, and finally *how* exactly it should be accounted for. The European standard EN 15978 [2] defines refurbishments as a part of the use stage in the life cycle of buildings. Further, in refurbishment projects without a previous LCA, the standard allocates refurbishment impacts to the initial product stage, dividing the building life cycle into two life cycles: one before refurbishment and a new one after refurbishment, as illustrated in **Figure 1**. This raises the question of how to allocate material impacts between the two consecutive life cycles. Methodological choices for the second life cycle are key, because they provide the foundation for deciding if the building should be demolished and replaced by a new one, or which interventions should be made in the refurbishment.

Previous literature reviews on refurbishment-LCA exist [3–5] but lack a focus on allocation approaches and modelling used for the existing building materials. The aim of this study is therefore to present and characterise different existing allocation approaches for LCA in refurbishments. Furthermore, the study highlights advantages and disadvantages of the analysed approaches from an LCA practitioner's view.

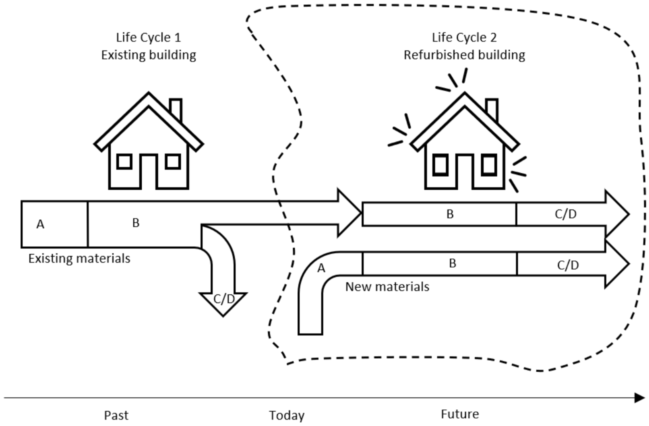

Figure 1. System boundaries for refurbishment (life cycle 2) can vary, and are relevant in terms of work load, building design, and benchmarking. The letters refer to the life cycle stages of a building defined in EN 15978 [2]: product and construction process (A), Use (B) end-of-life (C), and benefits and loads beyond the system boundary (D).

2. Method

A literature study was conducted to find studies that use and describe the allocation approach and modelling used for refurbishment. The goal was not to quantify how common the approaches are, but to identify studies that can illustrate the range of different allocation approaches and modelling of the existing materials in refurbishment projects. Literature was found using the following search string in Scopus: building AND renovation OR refurbishment OR retrofit AND "life-cycle assessment" OR lca OR "life cycle assessment" OR "ghg". The snowball approach was used to find additional relevant papers. Other papers known to the authors to be of relevance were included. This paper focusses on the two life cycles (before and after refurbishment).

The practical implications for LCA-practitioners were evaluated for each approach identified in literature. The evaluation includes considerations on work burden in relation to data collection and specific competences needed that may not be typical for an LCA-practitioner in the building industry who do not have environmental expert knowledge.

3. Results and discussion

In **Table 1** the different approaches are listed along with examples of literature using them. The first approaches are directly related to the allocation between the two life cycles, while the last approach relates to the modelling approach. The approaches are described in sections 3.1. to 3.4. Pros and cons from an LCA-practitioners point of view qualitatively estimated based on the authors expertise in the field are listed in the table and discussed in section 3.6.

Table 1. Allocation and modelling approaches for existing materials in refurbishment projects and evaluated pros and cons for the LCA-practitioner in relation to the methods.

Approaches	**Examples of approaches in literature**	**LCA-practitioner** + **Pros** − **Cons**
Allocation using 50:50, avoided burden, PEF	Obrecht et al. [6]	+ Shows the value of existing materials − Additional workload in mapping data from the existing building, and performing the allocation approach
Burden-free (and semi-burden-free)	Wijnants et al. [7] Hasik et al. [8] Rasmussen and Birgisdottir [9] Zimmermann et al. [10]	+ If end-of-life (EoL) of existing materials is included, it shows *all* impacts that happen from today and onwards + Correlates with CEN-standards, thus easier to implement in e.g. regulation + Less workload when EoL of existing materials is not included − Additional workload when EoL of existing materials is included − Challenges in biogenic accounting for global warming potential
Residual value or Depreciation	Wijnants et al. [7] Rasmussen and Birgisdottir [9] Obrecht et al. [11]	+ Shows the value of existing materials − Requires service life evaluation − Additional workload in mapping data from existing building
Adjusting for past production of existing materials	Bin and Parker [12] Potrč Obrecht et al [13]	− Requires advanced knowledge about previous production − Additional workload in mapping data from existing building and gathering historical data

3.1. Allocation using 50:50, avoided burden and PEF

As described in the introduction and illustrated in **Figure 1**, refurbishments can be considered a new building life cycle. However, this requires allocation between the impacts from the two consecutive life cycles if we want to assess the life cycles separately. Approaches for allocation from reuse and recycling of building materials have been investigated previously in literature [14–16], focusing mainly on product level. The common conclusion is that allocation approaches are not objective, and all have advantages and disadvantages. Allocation approaches deal with the distribution of impacts from production and EoL stage of reused and recycled materials [14]. The use stage is not included; thus, the service life of building products is not a part of these allocation approaches. Building products typically have the largest impact during production [17], making the allocation of the product stage the most influential impact to allocate [14–16].

Three commonly used allocation approaches are: 1) the 50:50 approach in which burdens from reuse/recycling are allocated equally between the first and second cycle in which the material is used, 2) the avoided burden approach in which burdens from reuse/recycling are allocated to the cycle reusing/recycling the material, and 3) the circular footprint formula (CFF) approach from the product environmental footprint (PEF) in which a factor-based distribution reflecting supply and demand between systems is applied. The application of the different approaches have shown to yield significantly different results[14–16].

These allocation approaches have been used to consider the reuse and recycling of materials, specifically in terms of design for disassembly, and other reuse in the future. However, Obrecht et al. [11] have recently considered them in the light of refurbished building components, where some materials are preserved in the refurbishment. The different allocation approaches for the reused or recycled content showed a significant difference in results in the second life cycle. The study also argues that the allocation approach should be chosen based on the goal and scope of the project, as they promote different incentives for decision-making. Some buildings may also undergo several refurbishments, influencing the allocation approach, and the results of the study. The allocation of a component between life cycles can be seen in **Figure 2**.

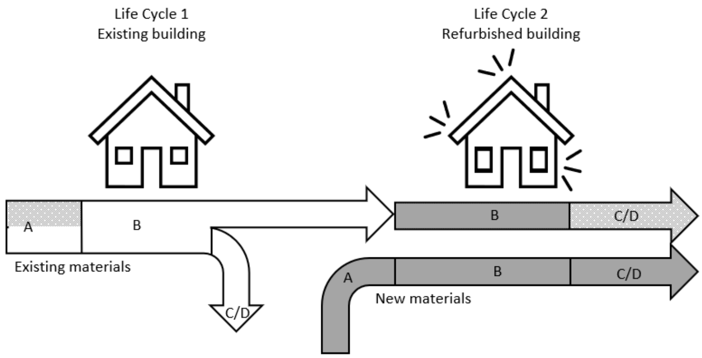

Figure 2. Existing materials that are reused or recycled and re-installed in the building, can be allocated between the first and second life cycle (light grey) using different methods. New materials and the use stage (B) of reused materials are in principle always included in life cycle 2 (dark grey).

3.2. *Burden-free (and semi-burden-free) approach*

The burden-free approach follows some of the principles given in the European standard EN 15804 [18]. Some variation in the method exists, but a common denominator is that the production of the existing material is always allocated to the first life cycle. As mentioned, allocation of reuse and recycling between life cycles can be done for production and end-of-life (EoL), but not for the use-stage, as this belongs to the life cycles where they occur [14]. Thus the use stage in the second life cycle (stage B) has to be accounted for even in a burden-free scenario [8]. However, this is not always done as it entails additional work by the LCA-practitioner, e.g., due to replacements of the reused materials which requires the estimation of quantities and impacts associated with the products. The use stage for existing materials is for instance not included in the case study by Rasmussen and Birgisdottir [9]. Hasik et al. [8] included the use stage in their case study as the only impacts from existing materials. Here the preserved elements were mainly structural, thus the impacts from the use stage (though not shown explicitly) are likely minimal.

Wijnants et al. [7] included both a scenario with EoL from the first life cycle and a scenario only with impacts from new materials. They found that environmental and financial impact of EoL from the existing materials were insignificant, accounting for 2% for refurbishment, and 3.5% for demolition with new construction. In Zimmermann et al. [10] all grey and hatched stages illustrated in Figure 3 have been included. EoL in the refurbishment scenario was insignificant, however, for the demolition and new construction scenario, it accounted for 12% of climate impact.

Which stages from the standard (A-D) the impacts belong to can also be discussed: For instance, EoL of materials that are not kept in the building are illustrated as C/D of the life cycle 1, but can also be considered as part of the refurbishment process, which belongs to stage A in the refurbished project (life cycle 2).

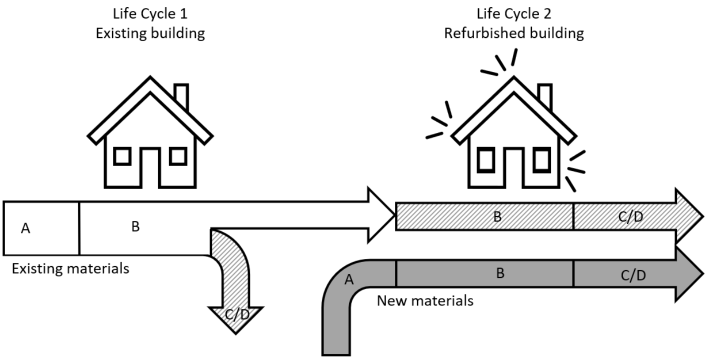

Figure 3. Burden-free approaches sometimes still include impacts from the existing structure. The hatched stages are occasionally included in burden-free approaches.

3.3. Residual value or depreciation

Residual value, also called the depreciation approach [7], can be used for allocation between the first and second life cycles. Residual value means the unamortized value of a product at a specific time – for instance at the time of refurbishment. In the context of LCA, it refers to the impact from production and EoL, which is ratioed between the remaining life span and predicted life span, also called reference service life, RSL. The method for determining residual values is the depreciation of impacts over time. This is commonly achieved by linear distribution.

Either all materials with residual value can be allocated to the second life cycle, or only the residual value from materials, that are reused in the building, see Figure 4. Rasmussen and Birgisdottir [9] used the latter approach to determine the environmental impacts of a refurbishment project (energy retrofit). Impacts were equally distributed across the RSL of the products and remaining unamortized impacts at the time of refurbishment are allocated to the second life cycle. This allocation resulted in larger impacts from the refurbishment than the traditional “burden-free” approach, however, greenhouse gas emissions were still well below those of new construction. A similar allocation approach was used by Wijnants et al. [7]. Here different refurbishment scenarios are compared, along with demolition and new construction scenario, and a scenario where nothing is done to the building. With the depreciation approach, the authors note that in their case study, the environmental cost of the existing components is only a minor part of the costs in the second life cycle. However, it still makes up more than 20% of the demolition and new construction scenario. Results also show that allocation with depreciation and the “burden-free” approach provided the same conclusions as to which scenario performed best. This could be because the residual value is the same in all scenarios. But the lifespan of the second building life cycle has a significant influence on the results, because of the balance between materials and energy impacts.

Obrecht et al. [11] consider the residual value *after* allocation between the two life cycles, as a way to consider the value of the element years into the first and second life cycle, and how different allocations approaches and time of refurbishment result in variation in this value.

Determining the residual value of elements that are reused or recycled within the refurbishment requires a time-consuming evaluation. Another important aspect pointed out by Obrecht et al. [11] is the significance of the RSL when determining the residual value of products. These values can vary greatly between RSL databases and have a significant influence on the results; thus, sensitivity analyses are often included in the assessments.

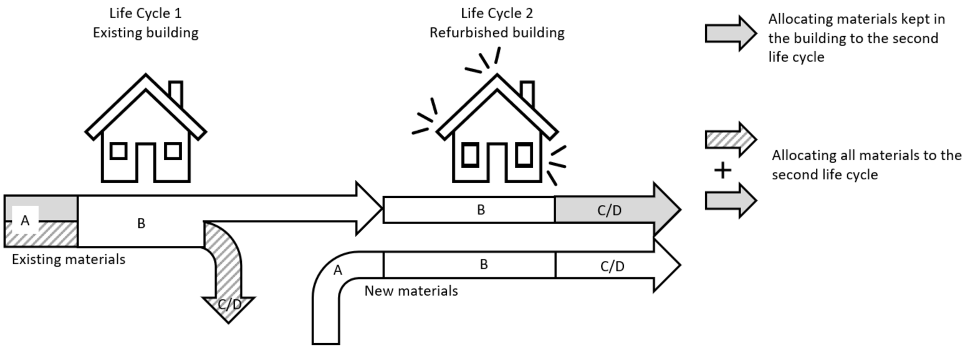

Figure 4. Allocation approaches in refurbishment can include only the reused materials (light grey), or all materials, that have residual value at refurbishment (both gray and hatched).

3.4. Adjusting for past production of existing materials

Impacts from material production were different in the past due to differences in manufacturing processes, transportation, and energy production. This can be accounted for in a refurbishment-LCA and links closely to the principles of dynamic LCA, where temporal inconsistencies are accounted for. While a dynamic approach to LCA is used for anticipating future changes, it may also be used for considering past impacts in refurbishment-LCA.

Bin and Parker [19] have estimated an existing building's impacts from the production one century ago, applying data from architectural historians, current manufacturers, and literature for determining energy and carbon emissions embodied in the materials. They conclude that impacts from the existing building are similar or lower than producing the materials today. However, Bin and Parker found that initial impacts were not as low as one might expect. This was due to the energy extensive brick production.

Potrč Obrecht et al. [20] assume that production processes have remained the same for materials. However, they have modified the electricity mix in current datasets, and adjusted the efficiency of electricity use. This was tested on materials in a case building from 1970 in Slovenia. The past electricity mix was remodeled based on the national mix at the time of construction, and there was assumed a 0.5% production efficiency increase per year. Results show a higher impact from the previous production of between 8.3% and 14.7% for the building components in the case building. Potrč Obrecht et al. highlight the importance of considering the electricity mix in all subprocesses to get a realistic result.

The two studies showed a higher and lower impact from adjusting for the previous production. It can be concluded that adjusting for past production may influence the results, though it may not be significant. Concerning implementation for an LCA-practitioner, these dynamic approaches will result in a high work load as data and tools to perform dynamic LCA is lacking.

3.5. Method considerations in studies

3.5.1. Suggested methods. Obrecht et al. [11], Hasik et al. [8] and Zimmermann et al. [10] all recommend and test different methods for refurbishment-LCA in their studies: Obrecht et al. [11] suggest a new methodology for calculating environmental impact and the residual value of refurbishment measures, to correctly assess components that are reused or recycled after refurbishment. Thus, they suggest including impacts from the existing building in the refurbishment projects, using allocation principles, and to consider the residual value of materials. They argue that by excluding the first life cycle, the benefits of refurbishment could be overestimated. The residual value shows how much damage is done to the environment if materials are removed prematurely. The decision of system boundaries in refurbishment projects influences the impacts that happen today. This includes decisions on the reuse and recycling of materials that leave the system during the refurbishment. If this is left out of the refurbishment-LCA scope, then the incentive to properly reuse or recycle materials that leave renovation projects is lacking and must be secured by other means such as waste regulation. Hasik et al. [8] do not include residual value or EoL of existing materials, but consider that environmentally preferable EoL processes should be chosen for the existing materials, thus their disposal could be assessed separately. The French building certification scheme HQE [21] try to encourage the reuse of elements that leave the system. Section 3.3. showed that the residual value of materials that are removed from the project can be allocated to the refurbishment project (acting as a "punishment" for not using the materials to their full extent / service life). However, in HQE this impact can be negated, if the materials are reused in a different building project, see Figure 5**Fehler! Verweisquelle konnte nicht gefunden werden.**. Similarly, the refurbishment project is ascribed with impact from the reuse of products from another project.

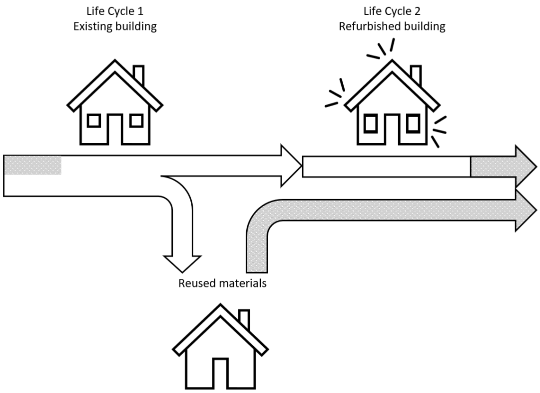

Figure 5. Allocating products that leave the system to the refurbishment project can be negated if products are reused in another system. This gives the incentive to make sure that materials are circulated in other projects. (Similarly reused products from other systems can be allocated to the refurbishment project).

Hasik et al. [8] present different methodological approaches to performing LCA on refurbishment projects. They suggest a method for comparative LCA for major renovations where only the use-stage of the existing building is included. They argue that this is more consistent with the scope of building-LCA for new construction, which does not typically include the EoL of the previous building on the lot – and possibly there was not even a building beforehand. Furthermore, they argue that renovation projects should not be penalized for decisions made for the existing building, which they have not been part of.

Zimmermann et al. [10] developed a framework for whole-building LCA when an existing building is the starting point. This includes impacts that happen from today and into the future building life cycle, but excludes impacts that have already happened. In this way, all future impacts are considered. They highlight that temporal perspective should be considered, such that demolition and new construction have a higher impact today, than preservation or renovation scenarios. While LCA is about considering impacts across the whole life cycle, mitigating impacts today should be of particularly high concern. This is both due to a higher uncertainty of impacts in future scenarios and because greenhouse gas emissions have to be cut rapidly to comply with the Paris agreement of limiting global warming to 1.5 degrees [22].

3.5.2. Influence of methodological choices. Wijnants et al. [7] and Rasmussen and Birgisdottir [9] tested whether the inclusion of existing materials had an impact on the results of their case studies: Wijnants et al. [7] wanted to focus on the methodological issue related to evaluating renovation interventions, such as the allocation of the existing materials between the life cycles before and after renovation. They found that this did not influence the overall decision related to renovation versus demolition and new construction. They also considered the role of estimating the building lifespan of the renovated project, which they found could affect the decision-making significantly. Rasmussen and Birgisdottir [9] tested the influence of the allocation approach in their study to consider methodological choices and its influence on their results. Although there was a difference in impact from allocating the initial impacts of existing materials to the second life cycle, the results were both lower than that of new construction, thus their overall conclusions remained the same.

3.5.3. Evolution of construction technology, efficiency, and electricity mix. Bin and Parker [19] and Potrč Obrecht et al. [20] both investigate the initial construction impact, but with slightly different goals: Bin and Parker [19] chose to model impacts from the existing building, both embodied and operational energy use, to compare them to the refurbished building, and to contribute with information to construction-technology comparison and debates on refurbishment vs replacement. While their method for adjustment for past production (as described in section 3.4) showed that the embodied energy of the initial building was higher than expected, it was overshadowed by the energy use from the building, and the potential savings from deep renovation. This led to a general recommendation to enhance the energy performance of buildings through renovation due to the high energy savings. Potrč Obrecht et al.'s [20] study wanted to understand how past production of materials influences future refurbishment measures by considering their influence on the residual value of materials. The residual value can inform on the value at a given time and can be used for decisions about preservation, reuse, or discarding.

3.6. Practical barriers from including existing building

Barriers in terms of implementation and method can be expected when including the existing building in the assessment. Assessing the type and quantity of existing materials is not a regular part of refurbishment projects and will add to consultancy costs. Only few deep refurbishment projects include a complete mapping of the building geometry and registration of materials using conservatory methods or 3D scans, which would add to the bill of quantity necessary for the LCA. Furthermore, an assessment of the remaining component service life is neither a part of refurbishment projects nor common in building condition reports.

The magnitude of this extra workload depends on whether all or only a selection of existing materials is included e.g. the share of demolished or reused components. In principle, the impact from the use stage of existing materials should always be included, however, this requires modelling of e.g. replacements. Furthermore, allocation approaches deviating from the EN 15804 cut-off approach [18] will be a practical challenge to implement, since existing generic or environmental product declaration (EPD)-data for building products already use this method [16].

Methodological challenges can also appear, e.g. for biogenic materials. This specifically applies in the burden-free approach where EoL of existing materials is included. If EPD data is used, following the product category rules from in EN 16485 [23], the biogenic carbon will not be neutral within the system, if only EoL of the existing materials are included (because biogenic carbon is only neutral if both production and EoL is included). Using the standardized data from EPDs thus propose a challenge in this approach. The newest update to the EN 15804 standard [18] which is gradually being implemented in EPDs will make this easier due to the separate accounting for biogenic global warming potential.

3.7. Future work
Future research should investigate the magnitude of impacts from the existing structure in refurbishment-LCA, depending on modelling and allocation approach, and their influence on decision making for different types of refurbishment projects.

This study estimated a considerable extra workload when including existing building materials in the assessment. Future research should therefore investigate possibilities for making refurbishment-LCA more feasible to implement for the industry. Currently, approaches for aiding material quantification through parametric models are being developed for simplifying refurbishment LCA [24, 25], but it is still a topic that needs to be investigated in future studies.

4. **Conclusion**
This study has presented and characterized different allocation approach and modelling in refurbishment-LCA. These included allocation of materials between consecutive life cycles, how to allocate impacts that leave the system and adjusting data for historical production.

Refurbishments can be considered as a new building life cycle. This requires allocation of the impacts between the cycle before and after refurbishment if we want to assess the life cycles separately. The allocation approach 50:50, avoided burden and product environmental footprint deal with the allocation of production and end-of-life impacts of reused and recycled material. The approaches have shown a significant difference in results in the second life cycle, and they promote different incentives for decision-making. The burden-free approach is different, as it does not allocate the production stage of existing materials to the refurbishment life cycle. Since the production stage typically has the highest impact, this approach will result in limited impact from existing materials. The residual value approach shows the unamortized value of a product at a specific time and can be used as an allocation approach in itself, or in combination with other allocation approaches. In the two studies that tested residual-value allocation against the burden-free approach, it did not result in different design incentives. Adjustment for historical impacts from the existing materials can be done and influences the result, though the significance appears to be limited.

The study has described the pros and cons of the different approaches to the LCA-practitioner. The main cons relate to the large workload related to modelling the existing building. Future studies should investigate the influence on results from the existing materials in the refurbishment-LCA using the different allocation and modelling methods. Furthermore, future studies should investigate methods to ease the workload for LCA practitioners.

References
[1] European Commission. Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. *Off J Eur Union* 2020; 26.
[2] CEN – European Committee for Standardization. *EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*. 2012.
[3] Vilches A, Garcia-Martinez A, Sanchez-Montañes B. Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy Build* 2017; 135: 286–301.

[4] Amini Toosi H, Lavagna M, Leonforte F, et al. Life Cycle Sustainability Assessment in Building Energy Retrofitting; A Review. *Sustain Cities Soc* 2020; 60: 102248.
[5] Schwartz Y, Raslan R, Mumovic D. The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies. *Renew Sustain Energy Rev* 2018; 81: 231–241.
[6] Obrecht TP, Jordan S, Legat A, et al. An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment. *J Clean Prod* 2021; 327: 129527.
[7] Wijnants L, Allacker K, Trigaux D, et al. Methodological Issues in Evaluating Integral Susatinable Renovations. *Proceedings of International Conference CISBAT 2015 □Future Buildings and Districts □Sustainability from Nano to Urban Scale* 2015; 197–202.
[8] Hasik V, Escott E, Bates R, et al. Comparative whole-building life cycle assessment of renovation and new construction. *Build Environ* 2019; 161: 106218.
[9] Rasmussen FN, Birgisdóttir H. Life cycle environmental impacts from refurbishment projects - A case study. *CESB 2016 - Cent Eur Towar Sustain Build 2016 Innov Sustain Futur* 2016; 277–284.
[10] Zimmermann RK, Kanafani K, Rasmussen FN, et al. LCA-Framework to evaluate circular economy strategies in existing buildings. *IOP Conf Ser Earth Environ Sci*; 588. Epub ahead of print 2020. DOI: 10.1088/1755-1315/588/4/042044.
[11] Obrecht TP, Jordan S, Legat A, et al. An LCA methodolody for assessing the environmental impacts of building components before and after refurbishment. *J Clean Prod* 2021; 327: 129527.
[12] Bin G, Parker P. Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home - The REEP House. *Appl Energy* 2012; 93: 24–32.
[13] Potrč Obrecht T, Jordan S, Legat A, et al. The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures. *Int J Life Cycle Assess* 2021; 26: 839–851.
[14] Allacker K, Mathieux F, Pennington D, et al. The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *Int J Life Cycle Assess* 2017; 22: 1441–1458.
[15] De Wolf C, Hoxha E, Fivet C. Comparison of environmental assessment methods when reusing building components: A case study. *Sustain Cities Soc* 2020; 61: 102322.
[16] Eberhardt LCM, van Stijn A, Rasmussen FN, et al. Development of a life cycle assessment allocation approach for circular economy in the built environment. *Sustain* 2020; 12: 1–16.
[17] Röck M, Ruschi Mendes Saade M, Balouktsi M, et al. Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation. *Appl Energy* 2019; 258: 114107.
[18] CEN - European Committee for Standardization. EN 15804:2012+a2:2019 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products.
[19] Bin G, Parker P. Measuring buildings for sustainability: Comparing the initial and retrofit ecological footprint of a century home - The REEP House. *Appl Energy* 2012; 93: 24–32.
[20] Potrč Obrecht T, Jordan S, Legat A, et al. The role of electricity mix and production efficiency improvements on greenhouse gas (GHG) emissions of building components and future refurbishment measures. *Int J Life Cycle Assess* 2021; 26: 839–851.
[21] GBC-france. HQE, http://www.hqegbc.org/home/ (accessed 14 February 2022).
[22] De Forenede Nationer. Parisaftalen. 2015; 24–45.
[23] CEN – European Committee for Standardization. *EN 16485:2014 Round and sawn timber – Environmental Product Declarations – Product category rules for wood and*. 2014.
[24] Kanafani K, Garnow A, Zimmermann RK, et al. Automated Life cycle inventories for existing buildings – a parametric reference model approach. *IOP Conf Ser Earth Environ Sci*.
[25] Decorte Y, Steeman M, Van Den Bossche N. Effect of a one-dimensional approach in LCA on

the environmental life cycle impact of buildings: Multi-family case study in Flanders. *Build Environ* 2021; 206: 108381.

Appendix D. Publication IV

Publication IV: **Automated life cycle inventories for existing buildings – a parametric reference model approach**. Kanafani, K., Garnow, A., Zimmermann, R. K., Sørensen, C. G., Brisson Stapel, E. & Birgisdottir, H. In: IOP Conference Series: Earth and Environmental Science, 2022, 1078

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Automated Life cycle inventories for existing buildings – a parametric reference model approach

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Abstract. Buildings account for 40% of global Greenhouse gas (GHG) emissions. In heating-dominated climates, most building-related emissions originate from building stock operational energy, especially from buildings constructed before energy requirements were introduced. Renovation can mitigate operational emissions, however, materials should be included to increase the mitigation potential. Life-cycle assessment (LCA) includes emissions from materials and energy but are time-consuming in renovations because BIM-aided approaches for automating inventories are inaccessible for existing building fabric. This paper proposes a parametric inventory-generator for existing buildings, which defines material quantities through few key variables, which are accessible in early design stages, and which relate to a reference model for a specific building type. The generated model includes LCA inventory data such as service life, replacements, and End of Life from a generic impacts database. The model is adjustable and can be supplied with predefined renovation interventions and new components. The proposed simplification has potential to facilitate modelling of LCA inventories for every existing building, and makes LCA feasible for more than deep renovations, offering a base for the proposed renovation pass by the EU commission. Future research will add building types and explore implementing default inventories based on cadastre data as public resource.

Keywords. Renovation, LCA, whole-life carbon assessment, early design, parametric model generator

1. Introduction

With the Paris-agreement [1] many countries have agreed on committing to limit global warming to 2.0 degrees with an aspiration to 1.5 degrees. The European Union member states have agreed to reduce GHG emissions by 70% in 2050 compared with 1990 levels. Carbon mitigation is especially relevant in the building sector, as it represents almost 40% of greenhouse gas (GHG) emissions [2]. Since 85-95 % of the building stock (EU) will still exist in 2050 [3], mitigating GHG emissions in the building stock is inevitable and strong policy instruments for more and deeper renovations are discussed in the EU Renovation Wave initiatives, including mandatory energy retrofits [3, 4].

The dominant method for determining whole-life building impacts is life cycle assessment (LCA) based on the EN 15978 [5] and related CEN TC350-standards, also being the key element in the European Commission's LCA scheme Level(s). However, it is commonly agreed that rules for LCA require a translation from the more theoretical definitions given in EN 15978, to practical implementation in actual policy schemes [6–8]. Taking into account the current premature state of LCA-implementation in the building industry, effective carbon regulation must include both a simplification of the EN 15978 scope, which is too comprehensive for application in specific building projects, and tools for efficient LCA workflows. Regarding method simplification, any of the currently emerging national carbon regulations for buildings apply some degree of method simplification [9–13], as whole-life carbon emissions are becoming a regular building performance indicator. Key to any building LCA tool is establishing and managing a building material inventory (building model), which is the most time-consuming procedure and therefore possesses a potential productivity improvement. Material inventories are required in all building LCA applications (Figure 1) and may include both existing and new components. Common for all LCA applications is that most building carbon emissions are determined in early project stages [14– 16].

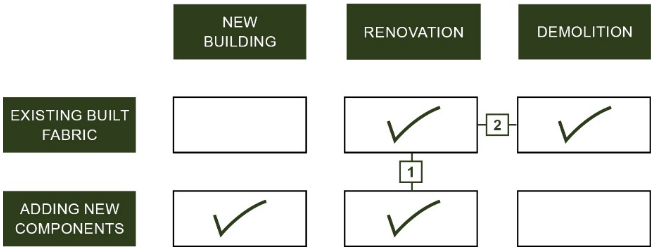

Figure 1. Need for material inventories in various LCA applications. Inventories of the existing built fabric can be reused in two ways, (1) for quantifying added components in renovations and (2) for inventorying a demolition case i.e. when comparing scenarios for renovation with demolition and new building

Known approaches for increasing productivity in generating material inventories include

1. Developing GHG reference emission values for on building or or building element level
2. Linking LCA with geometric models (3d CAD, BIM)
3. Developing generic product and component libraries
4. Deriving generic material quantities

Applying reference emission data are the quickest and simplest way of estimating carbon emissions of a building typology or parts of the building model, however they lack the possibility of controlling results and adjusting the LCA-model to project specific parameters. Since they do not provide an LCA-model, reference data cannot be reused in subsequent projects stages, which ultimately postpones the time-consuming modelling work to later stages.

Recent developments of linking LCA with digital design tools have shown the potential of becoming an industry standard. Even though digitalization has made these solutions more accessible, these links are not always the best choice, and some challenges remain to be solved [17, 18]. Most of all, integration of LCA in design models are restricted to projects with comprehensive BIM or 3D workflows, which is especially challenging in small projects and renovations.

Generic product and component libraries are useful in both new building and renovation LCA. More and more of these life cycle inventory databases are emerging [19–24], mostly in support of national whole-life carbon limits regulation. Generic products and component data help establishing an initial building model and allow estimating carbon emissions already in early design, where they can replace less determined or missing material quantities.

Carbon mitigation in existing buildings is achieved by cutting operational energy consumption and renewable energy supply. Necessary interventions include a certain amount of material flow in and out of the building, adding new environmental impacts to the building account. The design of optimum renovation interventions therefore needs consideration of the trade-off between operational energy savings and embodied materials impacts. This paper focusses on the embodied emissions, since operational energy methods are well-established.

However, there is a significant difference in workflow between renovation and new buildings. Most renovation LCA approaches include the existing building fabric in the assessment [25]. Quantifying the existing building fabric is necessary for inclusion in the building's future life cycle after renovation but is not a part of renovation processes. This extra workload might exceed the effort for modelling the actual intervention and cannot be justified by the magnitude of its carbon emissions, which will often be lower in deep renovations.

1.1. Problem and research aim

Despite offering significant potential for reduction of environmental impacts, the practice of renovation-LCA is not as widespread as LCA for new buildings. Barriers for the uptake of renovation LCA are lacking legal requirements, lacking method harmonization and not least the time-consuming registering of the existing building fabric. This is especially crucial in initial project stages or small-scale renovations, where the existing building fabric is not modelled in detail. Since the discussed existing approaches for simplifying the LCA process cannot be applied to quantifying the existing building fabric, renovation LCA either exceed project budgets or lack quality, both of which will hinder effective climate action.

This paper proposes a parametric inventory-generator for existing buildings. It is based on generic components and quantities calculated from a reference typology, which together provides a complete building model inventory. Input parameters must be simple and available to the practitioner in any renovation project. At the same time, it must deliver complete and detailed material quantities for allowing useful estimates of the final LCA in early design stages. Instead of a static black box benchmark, a dynamic model is required, where material choice and quantities can be adjusted depending on the specific project in the often-unique conditions with past layers of changes and renovations. Once the dynamic, structured building model has been generated, it should form the base for the LCA workflow during all remaining project stages. As the blueprint for the existing building has been generated, the method supports the process of adding renovation interventions to the building elements in question.

2. **Method**

A precondition for aiding inventories for existing buildings is an analysis of building typology, detailing and material use in the building stock, which then is used to develop a parametric model. This paper is selecting one building typology as a pilot case to illustrate the method but can be extended to other typologies and building ages. The pilot is masonry apartment building typology from 1850-1920, which is typical urban housing form in most cities in Denmark.

In a first step, drawings for six buildings from four different neighborhoods were retrieved from the public building register. Floorplans, elevations, sections and details were subsequently compared to define common typology characteristics, which are relevant for a Bill of Materials used in building LCA (Figure 2). This includes two types of information, firstly the composition and area of building elements relative to a reference unit, and secondly building geometry including building depth, floor height and roof type. The typology analysis was accompanied by an existing comprehensive building typology study [26].

The found components were compiled in a generic library for existing building components (Ex-library) as a background for the LCA tool LCAbyg [27]. The retrieved building geometry information was then used for developing a generic building model. In the pilot typology, a repetitive floor plan sequence was identified and then used as a modular unit to determine component quantities (Figure 2).

Other relationships between building geometry and material quantity, such as roof or basement level or the increasing wall thickness in lower floors, were defined in a set of constants. Definitions for both the module-based and other relationships are given in Tables 2 and 3.

By combining eight user input variables (Table 1) with building geometry information and the component quantities from the Ex-library, a complete building model of any given existing building within the typology can be generated. Typical renovation intervention components (Ren-library) were developed from available professional and industry information. Components in all libraries are composed from generic products from Ökobaudat [29], which is the product level library in the LCA tool.

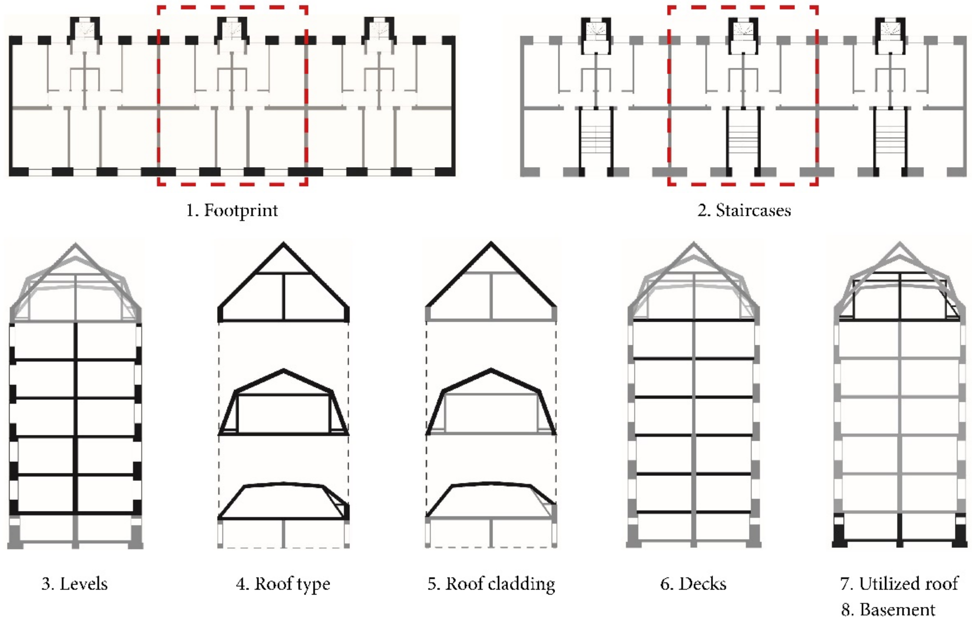

Figure 2. Generic case building. The modular unit is marked in red.

3. Results

Results of this project will be accounted for in different steps, which are explained individually in subsections. The project has introduced a new method for automatically generating inventories of the existing building fabric in renovation LCA (Figure 3). Viewed from left to right, the method for developing both component libraries and building typology constants is illustrated. The libraries with components for the existing fabric (Ex-library) allows composing a building model by providing all types of components and material choices, which are common for the building typology. To generate an existing building model, the user must define eight variables. Finally, a series of formula was developed, which combines the user input with the Ex-library and generates a fully detailed building model of the existing building fabric. It is then optional for the user to adjust element area or implement changes in the built fabric, which deviate from the original state. Since the model includes generic areas for all building elements such as walls and roofs, the generated building model can then be supplemented with specific renovation interventions from the Ren-library. Components in both libraries include quantities of building products in full detail and can be edited or replaced with user components in LCAbyg [27]. An international version in English is available. Since the tool also includes an extensive component library for new components, it supports the simple generation of comparing scenarios for preserving the existing building, renovation or demolition and replacement with a new building. Libraries, assumptions, and method for the inventory generator have been published in a background report [28].

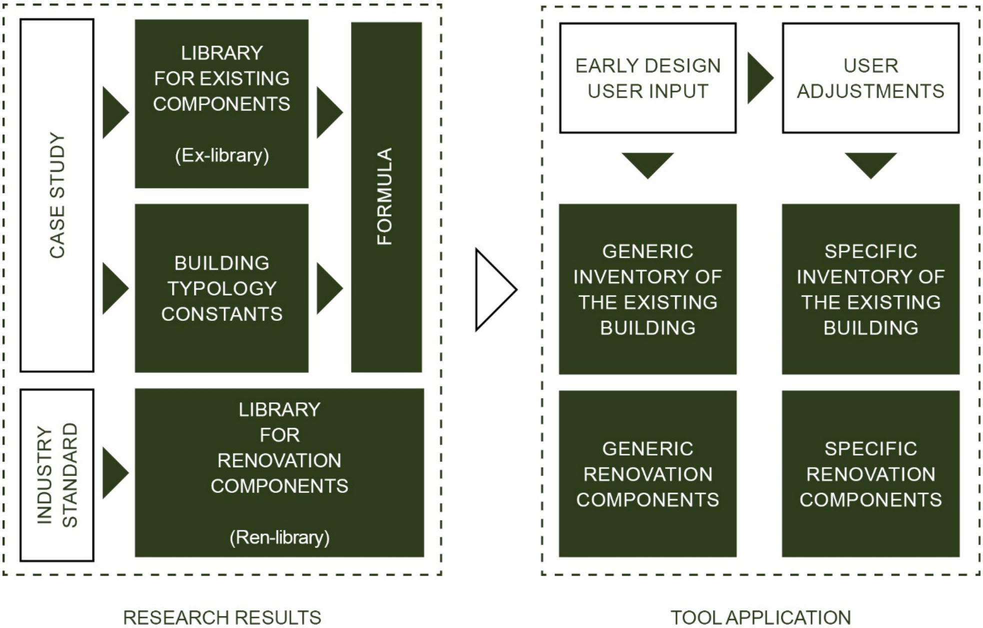

Figure 3. Development of the inventory-generator and component libraries (left side) and applied LCA process with incremental refinement from a user perspective (right side).

3.1.1. Ex-library (existing building fabric components). Components include both items, which are specific for the chosen building typology, many are relevant for other typologies as well. Each component has a description to help evaluate its suitability. Since the components are historic, all of the production stage is omitted. Components are assembled with generic building products from Ökobaudat [29], which is the core library in the LCA tool.

3.1.2. Ren-library (renovation intervention components). Interventions were developed for modelling the added materials to the building in renovations. The library covers the most common interventions, which include an energy retrofit of the typology's building envelope. Building services and other, non-energy related interventions are not included. The structure of the Ren-library is similar to the Ex-library, consisting of components modelled with generic products from Ökobaudat [29]. However, renovation interventions are defined as new constructions including impacts from the production stage, and pre-defined with scalable quantities, so that project specific needs determine the size of construction. This includes insulation type and thickness.

3.1.3. Building geometry generation. The typology study has resulted in a number of constants and geometric relationships in the building typology, which are used to determine the component area of this building typology. The eight key variables (Table 1) include building information that is accessible in early stages of a project and do not require extensive resources to obtain.

Table 1. Input variables required by the user.

No.	Variable	Possible input	Formula
1	Footprint	area (m^2)	input = x
2	Staircase	number	quantity staircase
3	Levels above ground	number	quantity levels
4	Roof type	1. Pitched 2. Mansard 3. Copenhagen roof	multiple choice
5	Roof cladding	1. Tiles 2. Slate 3. Zink	multiple choice
6	Deck type	1. Timber, clay-fill 2. Steel, concrete	multiple choice
7	Utilized roof floor	yes / no	
8	Basement	yes / no	

Table 2. Determination of building geometry through constants and user input variables.

Building geometry	Floor	Quantity	Unit	Status
Building depth	Regular floor	9,500	m	constant
Floor height	Regular floor	2,772	mm	constant
Basement height	Basement	2,046	mm	constant
Staircase area	Regular floor	16	m^2 / pcs.	constant * staircase number * quantity regular floors
Primary stair area	Regular floor	11	m^2 / pcs.	constant * staircase number * quantity regular floors
Secondary stair area	Regular floor	5	m^2 / pcs.	constant * staircase number * quantity regular floors
Staircase area	Ground floor	16	m^2 / pcs.	constant * staircase number
Secondary stair area	Roof floor	5	m^2 / pcs.	constant * staircase number
Secondary stair area	Basement	5	m^2 / pcs.	constant * staircase number

Table 3. Output area and calculation path from user input.

Generated area	Floor	Formula for generating areas	Share relative to footprint
Roof floor area	Roof floor	footprint - (secondary stair area * quantity staircase)	94,9%
Residential area	Regular floor	footprint - (staircase area * staircase number)	83,6%
Basement area	Basement	if yes = footprint - (secondary stair area * quantity staircase)	94,9%
Staircase area	Regular floor	primary stair * staircase number * (quantity levels -1) + secondary stair * staircase number * (quantity levels -1)	16,4%
Primary stair area	Regular floor	primary stair * quantity staircase * (quantity levels -1)	11,3%

Secondary stair area	Regular floor	secondary stair * quantity staircase * (quantity levels -1)	5,1%
Staircase area	Ground floor	staircase, ground floor * quantity staircase	16,4%
Secondary stair area	Roof floor	secondary stair * quantity staircase	5,1%
Secondary stair area	Basement	if yes = secondary stair * quantity staircase	5,1 %
Gross floor area (if 7: no)	All regular floors + Ground floor	residential area * quantity levels	
Gross floor area (if 7: yes)	All regular floors + Ground floor + Roof floor	(residential area * quantity levels) + roof floor area	

4.3.5. Example of possible building model (output). The following example (Table 4) illustrates a generated building model with all components, categorized by the elements they are classified in. The generated model represents the original state of construction, which can be edited afterwards for implementing deviations from the standard assumptions or past interventions.

Table 4. Example of generated building model.

Building element	Component name	Formula
Roof	Pitched roof, tiled	constant * roof floor area
Deck	Roof floor, deck	constant * roof floor area
Roof	Pitched roof, secondary stair, tiled	quantity * staircase number
Exterior wall	Pitched roof, primary stair	quantity * staircase number
Exterior wall	Ground floor, primary stair	quantity * staircase number
Exterior wall	Basement, primary stair	quantity * staircase number
Exterior wall	Pitched roof, secondary stair	quantity * staircase number
Exterior wall	Ground floor, secondary stair	quantity * staircase number
Exterior wall	Basement, secondary stair	quantity * staircase number
Foundation	Foundation, secondary stair (M)	quantity * staircase number
Windows	Roof floor, primary stair, windows	quantity * staircase number
Doors	Ground floor, staircase, exterior door	quantity * staircase number
Doors	Roof floor, staircase, interior doors	quantity * staircase number
Stairs & ramps	Ground floor, primary stair	quantity * staircase number
Stairs & ramps	Roof floor, secondary stair	quantity * staircase number
Stairs & ramps	Ground floor, secondary stair	quantity * staircase number
Exterior wall	Pitched roof	constant * residential area
Exterior wall	5th floor	constant * residential area
Exterior wall	5th floor, parapet	constant * residential area
Exterior wall	4th floor	constant * residential area
Exterior wall	4th floor, parapet	constant * residential area
Exterior wall	3rd floor	constant * residential area
Exterior wall	3rd floor, parapet	constant * residential area
Exterior wall	2nd floor	constant * residential area
Exterior wall	2nd floor, parapet	constant * residential area
Exterior wall	1st floor	constant * residential area

Exterior wall	1st floor, parapet	constant * residential area
Exterior wall	Ground floor	constant * residential area
Exterior wall	Ground floor, parapet	constant * residential area
Exterior wall	Basement	constant * basement area
Foundation	Foundation (M)	constant * basement area
Foundation	Foundation (L)	constant * basement area
Windows	Basement, windows	constant * basement area
Exterior wall	Pitched roof, gable	quantity * 2
Exterior wall	5th floor, gable	quantity * 2
Exterior wall	4th floor, gable	quantity * 2
Exterior wall	3rd floor, gable	quantity * 2
Exterior wall	2nd floor, gable	quantity * 2
Exterior wall	1st floor, gable	quantity * 2
Exterior wall	Ground floor, gable	quantity * 2
Exterior wall	Basement, gable	quantity * 2
Interior wall	Ground - 5th floor, non-load-bearing wall	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (S)	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (M)	constant * residential area * (quantity levels)
Interior wall	Ground - 5th floor, load-bearing wall (L)	constant * residential area * (quantity levels)
Deck	Ground -5th floor, deck, timber	constant * residential area * (quantity levels)
Windows	Ground - 5th floor, windows	constant * residential area * (quantity levels)
Doors	Ground - 5th floor, interior doors	constant * residential area * (quantity levels)
Exterior wall	1st - 5th floor, primary stair	quantity * staircase number * (quantity levels -1)
Exterior wall	1st - 5th floor, secondary stair	quantity * staircase number * (quantity levels -1)
Windows	Ground -5th floor, primary stair, windows	quantity * staircase number * (quantity levels -1)
Doors	1st - 5th floor, staircase, interior doors	quantity * staircase number * (quantity levels -1)
Stairs & ramps	1st - 5th floor, primary stair	quantity * staircase number * (quantity levels -1)
Stairs & ramps	1st - 5th floor, secondary stair	quantity * staircase number * (quantity levels -1)
Interior wall	Pitched roof, firewall	constant * (residential area / 2)
Interior wall	5th floor, firewall	constant * (residential area / 2)
Interior wall	4th floor, firewall	constant * (residential area / 2)
Interior wall	3rd floor, firewall	constant * (residential area / 2)
Interior wall	2nd floor, firewall	constant * (residential area / 2)
Interior wall	1st floor, firewall	constant * (residential area / 2)
Interior wall	Ground floor, firewall	constant * (residential area / 2)
Interior wall	Basement, firewall	constant * (residential area / 2)
Terrain deck	Basement, deck	constant * footprint
Stairs & ramps	Basement, secondary stair	yes = quantity * staircase number

4. **Discussion**

The value of providing parametric inventory generators in an LCA tool depends on a balance between ease of required input seen from a user perspective and accuracy and adaptability of the generated inventory. Since the selected pilot case is a historic typology, which can be applied to LCA of renovations, demolitions and building stock screenings, ease of input was more important than accuracy of results. When developing inventory generator for new buildings, this balance may be different. Also, the assumed need for the presented inventory generator relies on the inclusion of existing building fabric in renovation LCA. However, the authors believe that this methodology will become a standard approach, since embodied building emissions in the existing materials are a natural part in future building regulation and building passports. Also, parametric material quantification can offer a bottom-up approach to material bank analyses on neighborhood or national scale. The method also relies on the existence of material quantity patterns in building typology. This has shown true in this pilot case of the historic apartment typology and has to be tested for other modern typologies, which might be more difficult to quantify with a rule- based approach or could require more variables. Finally, the method is not restricted to existing buildings, as LCA become standard practice in new buildings, there is potential for further expansion and higher level of detail in libraries for new components. In the near future, the principles of the generator could be used for screening or quickly generating building models in new buildings, where potential hotspots could be identified early in the design process.

5. Conclusion
The parametric inventory generator based on a pilot typology has the potential of making LCA more for certain applications and under certain preconditions. Automated inventories are useful when no building model or Bill of Quantity/Materials is available, which is typically the case in early project stages or in LCA with low detail requirements such as inventories of existing buildings in renovations, new building/demolition versus renovation scenario comparison or building stock material bank screenings. A parametric approach is best suited for typologies with clear repetitive patterns in geometry and layout such as many apartment and office buildings. For more irregular typologies a statistical approach based on a large number of cases might be more appropriate.

References
[1] De Forenede Nationer 2015 *Parisaftalen 2015* p 24–45
[2] IEA 2019 *Global Status Report for Buildings and Construction 2019* vol 224 ISBN9789280737684
[3] European Commission Renovation Wave for Europe - Greening Our Buildings, Creating Jobs, Improving Lives 2020 *Off. J. Eur. Unionfficial J. Eur. Union 2020* p 26
[4] Commission T E, 2021 *Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast)*
[5] CEN – European Committee for Standardization, 2012 *EN 15978: Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method*
[6] De Wolf C, Pomponi F and Moncaster A 2017 Measuring Embodied Carbon Dioxide Equivalent of Buildings: A Review and Critique of Current Industry Practice *Energy and Buildings* **140** pp 68–80 doi:10.1016/j.enbuild.2017.01.075
[7] Schlanbusch R D, Fufa S M, Häkkinen T, Vares S, Birgisdottir H and Ylmén P 2016 Experiences with LCA in the Nordic Building Industry - Challenges, Needs and Solutions *Energy Procedia* **96** pp 82–93 doi:10.1016/j.egypro.2016.09.106
[8] Soust-Verdaguer B, Llatas C and García-Martínez A 2016 Simplification in Life Cycle Assessment of Single-Family Houses: A Review of Recent Developments *Building and Environment* **103** pp 215–227 doi:10.1016/J.BUILDENV.2016.04.014
[9] Stichting Bouwkwaliteit 2019 *Determination Method - Environmental Performance Buildings and Civil Engineering Works 3.0*
[10] Bolig- og Planstyrelsen 2020 *Vejledning Om Den Frivillige Bæredygtighedsklasse*

[11] The Finnish Ministry of the Environment 2019 *Method for the Whole Life Carbon Assessment*

of Buildings ed M Kuittinen
[12] Kuittinen M and Häkkinen T 2020 Reduced Carbon Footprints of Buildings: New Finnish Standards and Assessments *Buildings and Cities* **1** pp 182–197 doi:10.5334/BC.30
[13] Norsk Standard 2018 *Method for Greenhouse Gas Calculations for Buildings - NS 37:2018*
[14] Basbagill J, Flager F, Lepech M and Fischer M 2013 Application of Life-Cycle Assessment to Early Stage Building Design for Reduced Embodied Environmental Impacts *Building and Environment* **60** pp 81–92 doi:10.1016/J.BUILDENV.2012.11.009
[15] John V 2013 *Derivation of Reliable Simplification Strategies for the Comparative LCA of Individual and Newly Built Swiss Apartment Buildings* doi:10.3929/ETHZ-A-007607252
[16] Marsh R, Rasmussen F N and Birgisdottir H 2018 *Embodied Carbon Tools for Architects and Clients Early in the Design Process* ed F Pomponi et al (Cham: Springer) ISBN 978-3-319-72796-7 https://doi.org/10.1007/978-3-319-72796-7_8
[17] Soust-Verdaguer B, Llatas C and García-Martínez A 2017 Critical Review of Bim-Based LCA Method to Buildings *Energy and Buildings* **136** pp 110–120 doi:10.1016/J.ENBUILD.2016.12.009
[18] Röck M, Passer A, Ramon D and Allacker K 2019 The Coupling of BIM and LCA—Challenges Identified through Case Study Implementation *Life-Cycle Analysis and Assessment in Civil Engineering : Towards an Integrated Vision* ed R Caspeele et al (London: Taylor & Francis Group) pp 841–846 https://doi.org/10.1201/9781315228914
[19] BMI Ökobaudat 2021-I 2021.
[20] baubook GmbH Baubook Eco2soft Available online: https://www.baubook.info/eco2soft/ (accessed on 26 November 2020).
[21] SYKE; YM Emissions Database for Construction Available online: https://co2data.fi/ (accessed on 27 February 2022).
[22] Boverket Boverkets Klimatdatabas Available online: https://www.boverket.se/sv/klimatdeklaration/klimatdatabas/klimatdatabas/ (accessed on 27 February 2022).
[23] Kanafani K, Zimmermann R K, Rasmussen F N and Birgisdóttir H 2019 Early Design Stage Building LCA Using the LCAbyg Tool: New Strategies for Bridging the Data Gap *In Proc. IOP Conf. Ser.: Earth and Environmental Science* **323** 012117 (Graz: Institute of Physics Publishing) doi:10.1088/1755-1315/323/1/012117
[24] Kanafani K, Zimmermann R K, Rasmussen, F N and Birgisdóttir H 2021 Learnings from Developing a Context-Specific LCA Tool for Buildings—The Case of LCAbyg 4 *Sustainability* **13** 1508 doi:10.3390/su13031508
[25] Zimmermann R K, Rasmussen F N, Kanafani K, Eberhardt L C M and Birgisdóttir H 2022 Allocation Approaches and Modelling in LCA for Building Refurbishment *In Proc. SBE 22 Berlin*
[26] Engelmark J 1983 Københavnsk Etageboligbyggeri 1850-1900: En Byggeteknisk Undersøgelse *SBi-Rapport* **142**
[27] Zimmermann R K, Birgisdottir H, Sørensen C G, Kanafani K, Tozan B and Stapel E B 2020 *LCAbyg 2020*
[28] Kanafani K, Zimmermann R K, Stranddorf L K, Garnow A and Birgisdottir H 2022 *Eksempelbibliotek til LCAbyg* ISBN 978-87-563-2019-1
[29] BMI Ökobau.Dat 2021-I 2021.

Appendix E. Publication V

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Article

BIM-Based Life Cycle Assessment of Buildings—An Investigation of Industry Practice and Needs

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Abstract: The climate debate necessitates reducing greenhouse gas emissions from buildings. A common and standardized method of assessing this is life cycles assessment (LCA); however, time and costs are a barrier. Large efficiency potentials are associated with using data from building information models (BIM) for the LCA, but development is still at an early stage. This study investigates the industry practice and needs for BIM–LCA, and if these are met through a prototype for the Danish context, using IFC and a 3D view. Eight qualitative in-depth interviews were conducted with medium and large architect, engineering, and contractor companies, covering a large part of the Danish AEC industry. The companies used a quantity take-off approach, and a few were developing plug-in approaches. Challenges included the lack of quality in the models, thus most companies supplemented model data with other data sources. Features they found valuable for BIM–LCA included visual interface, transparency of data, automation, design evaluation, and flexibility. The 3D view of the prototype met some of the needs, however, there were mixed responses on the use of IFC, due to different workflow needs in the companies. Future BIM–LCA development should include considerations on the lack of quality in models and should support different workflows.

Keywords: life cycle assessment (LCA); building information modeling (BIM); environmental impact assessment; sustainability; building life cycle; integrated design process; digitalization; greenhouse gas emissions; IFC; visualization

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1. Introduction

The climate crisis necessitates an intensive investigation into reducing greenhouse gas (GHG) emissions. Here, buildings have a large reduction potential, as they are responsible for 38% of the energy and process-related GHG-emissions, globally [1]. To reduce the environmental impacts, life cycle assessment (LCA) of buildings is increasingly used. LCA is a widely used and accepted method of assessing the environmental performance of buildings. Moreover, LCA will in the near future become a mandatory requirement in several European countries such as Denmark, Finland, France, and Sweden [2,3]. However, the complexity and the time-consuming work related to LCA has often been considered a barrier [4–6], which now has to be overcome. Consequently, the efficiency potentials from using building information modeling (BIM) has gained attention in the literature [4,7], where several strategies for the workflow exist [7,8]. However, BIM–LCA is still at an early stage [7] and research on the topic is limited [4]. Some areas where research is lacking concern user-friendly platforms to assist in integration [4]. Further, to enhance interoperability between tools, integration methods with open file formats such as industry foundation classes (IFC) should be considered [4], which is currently less common in literature case studies [7].

The life cycle perspective is important because it includes considerations of material impacts. Due to previous years' political focus on reducing the operational energy use of new buildings, the impacts from materials have shown increasing importance [9–14].

The LCA method is described in ISO standard 14,040 and 14,044 [15,16] and, specifically for buildings, in the European standard EN 15,978 [17] from CEN TC350. Several nations have made their own method specifications considering the national contexts [2]. Life cycle assessment is used in sustainable certification systems [3,18,19], but several countries are considering or have decided to include limit values for GHG-emission in legislation, such as Denmark recently adopted [20]. Time and cost are part of the considerations from clients and legislators. Since some find the complexity of LCA high [21–23], this can be a barrier in the prioritization of LCA in the building industry. Especially for the early design stages, it can be an advantage to make LCAs quickly and often in order to support an iterative design process [24–26]. BIM can simplify the establishment of the life cycle inventory (LCI) for the LCA by eliminating the need to reenter information that is already available in the building model. Several studies have focused on BIM–LCA, but not through an industry perspective, where information is relevant for practical implementation in industry. The use of BIM in the industry is in continuous development. The use of BIM for public procurement is supported through EU directive 2014/24/EU [27], with national legislations [28]. In several countries, including Denmark, the use of BIM is required for public procurement of buildings, and the delivery must happen through IFC, which is an open interoperability standard [29,30] for architecture, engineering and construction (AEC), and facility management (FM). Several BIM–LCA studies have focused on IFC to support interoperability [31–34], however there is still a challenge with the poor design of the models [4,35]. This challenge could be addressed through a transparent and visual BIM–LCA approach. Here, some studies on BIM–LCA have focused on visualizing data from LCA directly in the model [36–38]. Further, some existing tools work with both IFC and visual interface such as the EveBIM in connection with Elodie [39], and the 6D-BIM-Terminal [34]. They use different approaches and focus on national contexts and specific situations, such as on the tendering stage. IFC and 3D view are also used in a Danish context, where a prototype has been developed to represent the workflow.

While prior studies have focused mostly on published academic case studies [4,7], BIM–LCA has become more common in industry practice. However, few studies on the practical use of BIM–LCA in the industry exist. The aim of this paper is to investigate this research gap by examining industry practices and needs in BIM–LCA. This includes the specific challenges related to the design of the models, and feedback on a prototype developed for the Danish context focused on the use of open neutral file formats and 3D view. “BIM” can be used to refer to more information-heavy tools and processes, but will in this study also include more simple, geometry modeling tools. Research questions in this paper are: (1) What workflow and challenges are related to BIM–LCA in industry practice? (2) What are needs for BIM–LCA in industry and are they met through the Danish prototype using open neutral file-formats and 3D view?

2. Background

2.1. Data Requirements for LCA of Buildings

While digital building models have an obvious advantage in creating the bill of quantities (BoQ), it is not the only data input required for an LCA. Following the terminology and method from European standard EN 15,978 [17], examples of additional data are operational energy and water use, service lives of products, transport, and maintenance and repair. These cover the different life cycle stages in order to determine the LCI, see Figure 1. Cavalliere et al. [40] have made an in-depth structure of relevant information to a BIM–LCA workflow. Furthermore, life cycle impact assessment (LCIA) has to be made, or an LCIA database for, e.g., building products, can be used. Different databases are available, and their use is typically connected to the choice of LCA-tool [41]. Since local adjustments in methodology for the building LCA exists [11], different data may be necessary depending on the context and goal of the LCA. These additional data can either be contained in the building model, or need to be added later on, for instance in an LCA-tool.

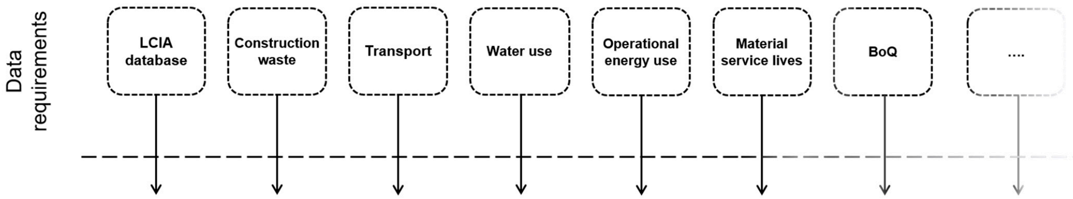

Figure 1. Examples of data requirement for LCA of buildings. Requirements and data structure can depend on the goal and context of the LCA.

2.2. Approaches for Integrating BIM and LCA

The literature distinguishes between adding environmental data into the building model, and only extracting information, such as the BoQ from the model [42,43]. Further, Wastiels et al. [8] categorize BIM–LCA integration into five approaches. These approaches also include the approach where LCA information is added to the model. This "enriched BIM" approach has the advantage that less information for the LCA needs to be manually attributed later on, thus supporting an automatic or semi-automatic workflow, which will greatly reduce human error [33]. Furthermore, centralizing data in the model can be an advantage in future uses of the model, such as facility management where an LCA may need to be redone [33]. Challenges for this approach are that the working environment for exchange of this information has to be established [33], including what information and where it should be attributed in the model, as well as how the data can be exchanged. Moreover, the work associated with changing a material in the model, in order to investigate different design solutions, may be larger than in an LCA software [8]. The most common approach in the literature is the "quantity take-off" approach [7]. Here, the BoQ is exported from the building model and then connected to an LCA software. The processes within the quantity take-off approach can range between manual and automated, depending on the use of different software for automation of the process. However, the manual process is the most common approach [7]. The nature of the approach is simple, but an iterative design process can be difficult, due to the manual processes involved. Further, the workload from manual processes can be extensive. The third approach from Wastiels et al. [8] is the "import of geometry into the LCA software", for example by using IFC for data exchange. An advantage of this approach is that IDs for the objects are used in the data exchange. This makes it easier to update the LCA without matching geometry and environmental data all over again. The fourth approach applies an intermediate "viewer" in a 3D environment, where information from, e.g., the IFC, is matched with environmental data. This approach has the same advantage with the use of IDs as the previous approach. Further, the match can happen within a 3D environment. For the previously mentioned approaches, there was no visual connection to the 3D environment of the building for the processes of matching data or visualizing results. The last approach also uses the 3D environment. This is the "LCA plugin" for the BIM software. Here, the BIM software automatically provides the 3D environment for matching and visualizing results dynamically for an iterative design process. The five approaches can be seen in Figure 2.

2.3. Data Exchange in BIM–LCA

The above-mentioned approaches are distinguished by their overall workflow; however, a crucial dimension is the type of data exchange. The data exchange within the tools available to the practitioners can limit their options for workflow.

Interoperability is typically the goal within data management between software solutions, to allow for easy exchange of data between software. Laakso and Kiviniemi [30] distinguish between the direct interoperability and open interoperability standards. An example of the open interoperability standard is IFC. The IFC schema is a standard, open, and vendor-neutral data model, describing the built environment [44]. Using a standard structure requires all relevant software to translate their data into the standard structure, thus creating a common language for all software to exchange data. For BIM–LCA, it is important to consider if the standard structure can contain the data you want to extract from your model, as described in Section 2.1. Using a standard data structure will always restrict how data can be described, and thus used in the building performance tools [45]. However, data interoperability using an open standard data structure has obvious advantages as it reduces the number of times data need to be translated [30], see Figure 3. In principle, the standard data structure can be used in all five approaches mentioned in Section 2.2, except the plugin solution.

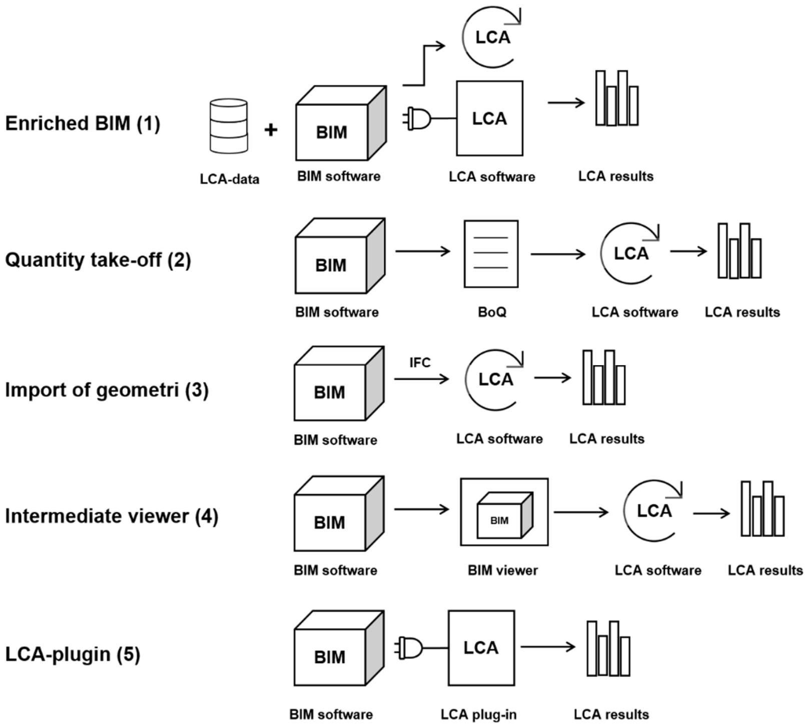

Figure 2. Five approaches to integration of BIM–LCA, as defined by Wastiels et al. [8].

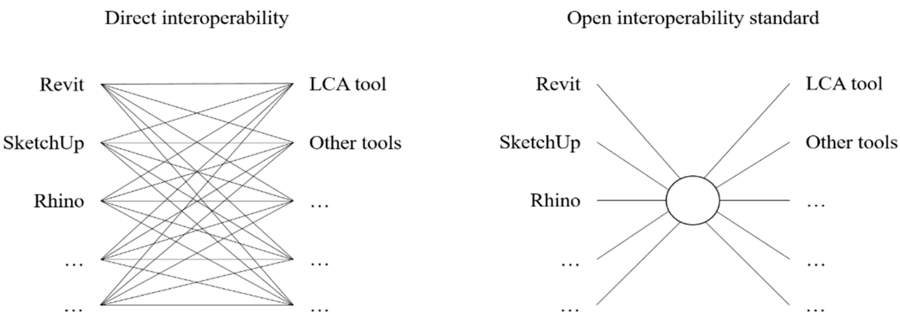

Figure 3. Data exchange from digital building model to LCA-tool using open interoperability standard and direct interoperability.

Alternatively, data can be transferred via direct interoperability, which requires some openness from the software providers in data structure [30]. This can be a challenge when proprietary data schemas are used. However, with an open data structure, data can be exchanged using, for instance, a file format to the target schema needed in the LCA. Open file formats that have been used for LCA are, for instance, xlsx [7]. These formats are typically used in approach 2 (quantity take-off), but can in theory be used for all above defined approaches, depending on the chosen data structure. The difference between this and the open standard data transfer is that it is not standardized, thus all transfers between tools, in principle, need to be made individually from each building model software to the LCA-tool, instead of using a common structure, see Figure 3.

Furthermore, software can provide the possibility of using plugins via an application programming interface (API) to exchange information with the software. An advantage of plugins is that it can add functionality to the original software, for instance, by visualizing results and receiving dynamic feedback on design changes within the building model environment. The plugin middleware can also select the specific data needed from the model for the data exchange with the LCA tool. Popular plugin solutions in the building sector are visual programming languages (VPL) [46], such as Grasshopper [47] and Dynamo [48], which make programming more available to architects and engineers. Plugin solutions can work alone without external dependencies, or as a bridge to an external LCA-tool. Approach 5 from Section 2.3 is defined as the plugin solution, however, a plugin can also work in connection with intermediate data schemas or formats. For example, VPL can be used to extract quantities and create an xlsx file, which can then be transformed to the LCA-tool data schema.

Some disadvantages of direct transfer are handling of software versions and errors in translation [30]. Furthermore, the plugin will only work with the specific software for which it is developed.

2.4. BIM–LCA at Different Design Stages

Data exchange in BIM–LCA can happen at different design stages where information in the models varies. Even within the same model, the level of development (LOD) can vary [49]. In early stages, the data for LCA from the building model is limited, and may not contain information on materials, for example. Conducting BIM–LCA at different LOD has previously been addressed in the literature [37,49–52]. Cavalliere et al. [49] and Röck et al. [37] suggest the use of predefined components based on the LCIA database for building materials when specific quantities are not known. For even earlier stages, average data for components or elements is suggested [49]. Predefined elements and components have also been suggested for early design LCA in general [2,21,24].

2.5. Prototype with Workflow for BIM–LCA

2.5.1. Context

A prototype has been developed in a Danish context as a possible workflow for BIM–LCA. The prototype only has some key features implemented, as well as some of the interface in order to give an idea of the functionalities. For the Danish Voluntary Sustainability Class [53] and the Danish adaption of DGNB (Deutsche Gesellschaft fur Nachhaltiges Bauen) [54], it is mandatory to use the environmental product declaration (EPD) or use the LCIA database, Ökobaudat [55]. Thus, one of the main goals for the BIM–LCA integration process is to gain information on material quantities and match the information with environmental data. The information is connected to the Danish national tool, LCAbyg [2,56].

2.5.2. Workflow

A prototype for BIM–LCA was developed to meet some of the challenges associated with poor design of models. The prototype was developed using the "viewer" approach as described in Section 2.2., but also closely related to the "import of geometry" approach, because the prototype is closely connected to the dedicated LCA software. The general idea of the developed prototype is: (1) the use of standard and open file-based exchange with flexibility in data input to support use across different design stages; (2) create a visual interface in order to enhance the quality and documentation of BIM-based LCA, and to support an iterative design process. The workflow is shown in Figure 4. From the building-model software, the data is exported to an open file format. This format is imported into the prototype, where the necessary information is added in order to perform the LCA, including matching the BoQ with LCIA data. The matching of BoQ with LCIA data happens manually or semi-automatically in the 3D environment based on the information available from the model, and the library of LCIA data. The semi-automatic process consists of suggestions of matches based on previous matches or material names. Further, objects with identical material composition can be grouped together and matched to LCIA data using names, classification, IFC-structure, shape, etc. This process can be further automated if information from the LCIA library elements have been implemented in the building model, following the approach of “enriched BIM”. In the 3D view, the object placement and quantities can be visualized. The LCA is carried out in the Danish LCAbyg-tool. LCAbyg is connected to the prototype through direct interoperability in python, using JSON-format to exchange information with LCAbyg. The prototype can be used to visualize results from the LCA directly in the 3D-model.

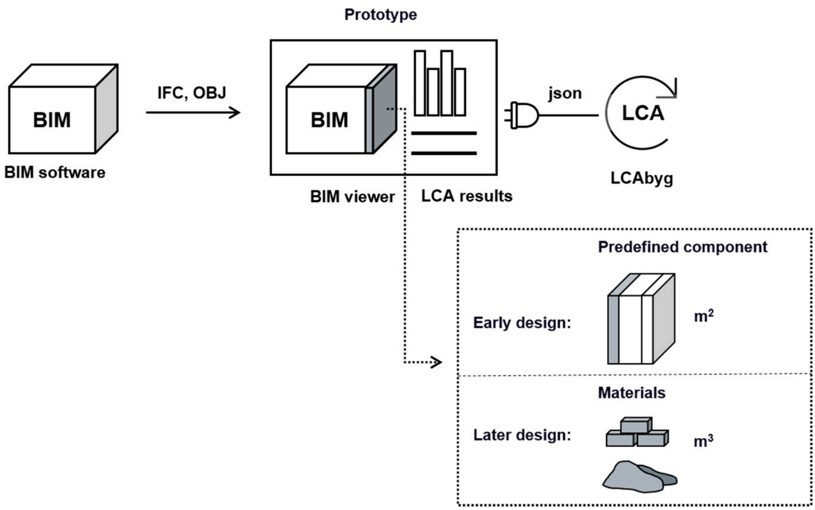

Figure 4. Workflow for BIM–LCA in the prototype. At different design stages, it is possible to work with different types of available information from the model.

2.5.3. Use across Different Design Stages

Due to variations in LOD of models during a building project, the prototype uses predefined components as described in Section 2.4. The user can match predefined components with the quantities in the model. All quantities are calculated and available in the prototype tool, thus it is possible to use the quantities that are relevant at the current design stage of the building model. In earlier stages with low LOD, the material information is likely not modelled. Here, environmental data for predefined components or elements can be matched with areas extracted from the building model. Predefined components are a part of the library in the Danish LCAbyg tool [57,58]. At later stages, the specific material quantities can be extracted from the digital model, or added within the prototype. This is illustrated in Figure 4. Results are provided through the LCAbyg tool.

2.5.4. Open File-Based Data Exchange

Open, file-based exchange was chosen as the data exchange in order to support a wide range of software for the digital models without creating middleware for each individual building model software.

For the prototype, two file formats have been selected for the data exchange: the IFC schema for the more complete data exchange, or OBJ for a limited data exchange. IFC is an open standard data model for AEC and FM, and can be represented through a file-based exchange [30]. OBJ is an open file format for describing 3D geometry. OBJ is strictly geometry, whereas IFC contains object based information which can store a large variety of data on the building. The information available in the IFC depends on the Model View Definition (MVD) [44] and can be different depending on the used building model tool, or the selections the user makes when they export their model to IFC. A specific MVD can be made for the data exchange, and has been developed in other studies [32,33,59]. However, for now the prototype will not require any specific information in the IFC. This way, the tool will be able to support all IFC models, no matter how they have been processed previously by software and users. The OBJ can act as a practical alternative to IFC because the process of import and export is faster than IFC, and the limited data exchange of OBJ will likely be enough for the early design stages where geometry is the only information available in the building model. Furthermore, export to IFC is not always accessible in the design tools (see Table 1). IFC and OBJ both use unique IDs for objects, making it possible to have an iterative process in the building design, without repeating the manual processes, as described in Section 2.2.

Table 1. Export options for Industry foundation classes (IFC) and geometry file format OBJ from different model software.

Model Software	IFC	OBJ
Revit	x	x
Rhinoceros	x [2]	x
Sketchup	x [1]	x [1]
ArchiCAD	x	x
AutoCAD	-	x [2]
Vectorworks	x	x

[1] Not available in the free version. [2] Requires purchasing of plugin.

2.5.5. Visual Interface

The visual interface in the prototype was achieved through an interactive 3D view of the building. See Figure 5. In this view, it is possible to navigate similarly to other 3D tools (zoom, rotate, etc.). When the user targets an object, the available information for the LCA is shown, such as quantities and material information. IFC and OBJ can both provide 3D-object information, necessary to visualize the building. The visual interface is where the BoQ is matched with LCIA data. Further, the 3D interface can be used to visualize results from the LCA. It is also meant to give a better understanding of the origin of the BoQ, and if there are collisions, missing or wrongly categorized objects, or other errors. The modelling errors become easier to find when they are visualized in the 3D model. The prototype calculates the quantities, but the user can also choose to use quantities from the original building-model software if they are included in the IFC. Moreover, it is always possible to overwrite the quantities or other information from the model.

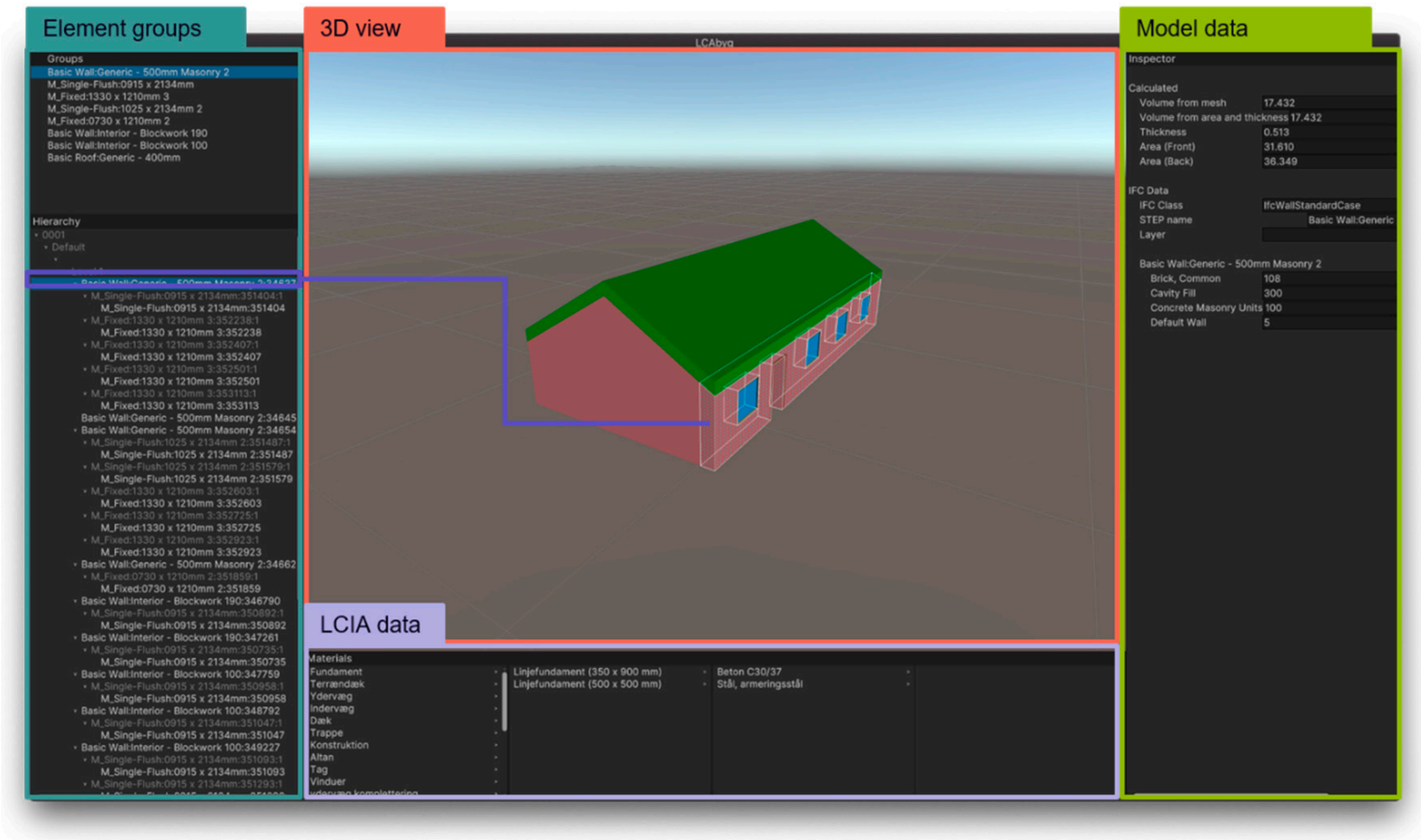

Figure 5. Prototype interface with 3D view of the building.

3. Materials and Methods

Qualitative Interviews

Data in this paper is based on qualitative in-depth interviews with companies who perform LCA of buildings. The goal of this method is to understand the company perspective on performing LCA of buildings, such as their current practices and motivation behind them, as well as demands for better workflow and feedback on the presented prototype.

The qualitative interviews consist of eight semi-structured interviews with companies in the Danish building sector, who offer LCA of buildings as a service. The companies were selected to represent a variation of company types with consultant services, from architect, engineering, and contractor firms. For further details, see Table 2. Contact with the companies had already been established through previous projects with LCA in the building industry. Prior to the interview, the themes of the interview were given to a contact person in the company and they were prompted to bring relevant informants from the company to the interview. Further, the questions were sent to the companies prior to the interviews, to give them an opportunity to prepare, or ask others in the company if they didn't have the answers themselves. The semi-structured interview focused on the following questions. Prior to the last question on the list, a presentation of the developed prototype was given:

- Which digital building model tools ("BIM") and LCA-tools do you use today?
- How is the BIM–LCA workflow in the company today, and why?
- How do you work with BIM in relation to LCA? E.g., use of discipline models;
- What challenges do you face in BIM–LCA?
- What is most important for a good BIM–LCA workflow? E.g., quick, automation, ease of use, transparency/quality assurance, flexible workflow, precision of data, visual/3D view, evaluation of design solutions, understand LCA and material impacts.
- Does the prototype satisfy these important aspects? What does it meet/doesn't meet, and why?

Table 2. Overview of the company type and informant profiles in the eight semi-structured interviews.

Interview	No. of Informants in Interview	Profiles	Company Type	No. of Employees in Denmark (in Ranges)
A	2	Engineers	Consulting engineers and architects	3000–3999
B	2	Engineer and design engineer	Consulting engineers and architects	1000–1999
C	3	Engineer and design engineer	Consulting engineers	100–199
D	1	Engineer	Consulting engineers	500–999
E	2	Engineer and architect	Consulting architects	100–199
F	1	Architect	Consulting architects	0–99
G	2	Engineer and architect	Consulting engineers and architects	3000–3999
H	2	Engineers	Contractor and consulting engineers	1000–1999

The interviews were analyzed and categorized using a combination of deductive and inductive coding technique [60]. The deductive coding technique is based on the theoretical background, and the inductive coding technique arose from informants discourse. The purpose of this is to understand the companies' workflow in relation to the existing literature on, e.g., the BIM–LCA approaches presented in Section 2.2, while including themes that arose from discussions with informants, such as the challenges they meet in BIM–LCA.

The eight interviews were comprised of 15 informants and were carried out in November and December 2020, and January 2021. The informants were engineers, architects, and design engineers. They covered informants with knowledge on LCA of buildings and, for some companies, informants that work across disciplines with a focus on sharing and using digital building information.

As stated above, the companies represent a broad variety of professional profiles and companies. The companies cover large and medium size companies, but not small or one-man businesses. Due to the size of the interviewed companies, they cover a large part of the Danish AEC industry, but it should be noted that the building industry in Denmark also consists of many smaller companies [61,62]. For this research, smaller companies were considered to have too little experience in BIM–LCA to give valuable input. The interviewed companies were chosen due to their knowledge and practical experience in performing LCA on buildings. The selected companies are part of an LCA expert group, who are consulted in relation to the development of the national tool for LCA on buildings, LCAbyg [2,56]. Due to their advanced knowledge in comparison to many other, and smaller, companies, their experience can inform in more detail on practical workflow and challenges as well as demands.

4. Results

4.1. BIM–LCA Workflow in Companies

The most commonly used BIM–LCA workflow in the companies is the quantity take-off approach, as presented in Section 2.2, and a few of the companies have started development on the LCA-plugin approach for the BIM software. However, the companies work differently within the approaches. Figure 6 illustrates how the individual companies work within the two approaches. All companies use direct interoperability for data transfer, but with some differences in approaches. Three of the companies use export of schemas from the BIM software, Revit, to Excel, in order to create the BoQs from the BIM. At times, company H creates the BoQs using a Dynamo script from Revit to an xlsx-file, along with company C and D. Here, company B uses a C# script for the same process of creating an xlsx file. All the mentioned companies manually transport the BoQs in the xlsx file into the LCA software, LCAbyg, where the LCA is done. However, company D typically uses their own excel tool for the LCA, and only does the final calculation in LCAbyg.

Company E uses a semi-automatic BIM–LCA workflow, where the BoQs are created from a Rhinoceros-model (Rhino) using a Grasshopper script. A library with predefined constructions can be linked by the user to the BoQs in Grasshopper, and JSON (JavaScript Object Notation) files are created according to the target schema in the LCA software, LCAbyg. Company A also uses a semi-automatic BIM–LCA workflow, where the BoQ in excel is created from a Revit model using Dynamo or export to Excel. In the Excel file, they can match BoQ with IDs for LCIA data. Based on the xlsx-file, a script transforms the data to xml files according to the target schema in the LCA software, LCAbyg.

Currently, some of the companies are developing the LCA-plugin approach for the models, to use in the early design stage. Company C is working on a solution for early design stage, using Rhino and Grasshopper, and company D is working on a tool using Revit, Power-BI, and matching via classification codes. These are still under development, and have not been included in Figure 6. Company G has recently developed a plug-in solution for the BIM software, Revit, where LCA results can be shown dynamically as the user edits the Revit model. The environmental impacts from a library with predefined constructions are linked to the keynotes in the Revit model.

4.2. Data Used for BIM–LCA

A BIM model is naturally used in the BIM–LCA workflow; however, several other data inputs are used within the companies. Figure 7 illustrates the different sources of data used for building models and how, in most cases, this information is supplemented with additional data.

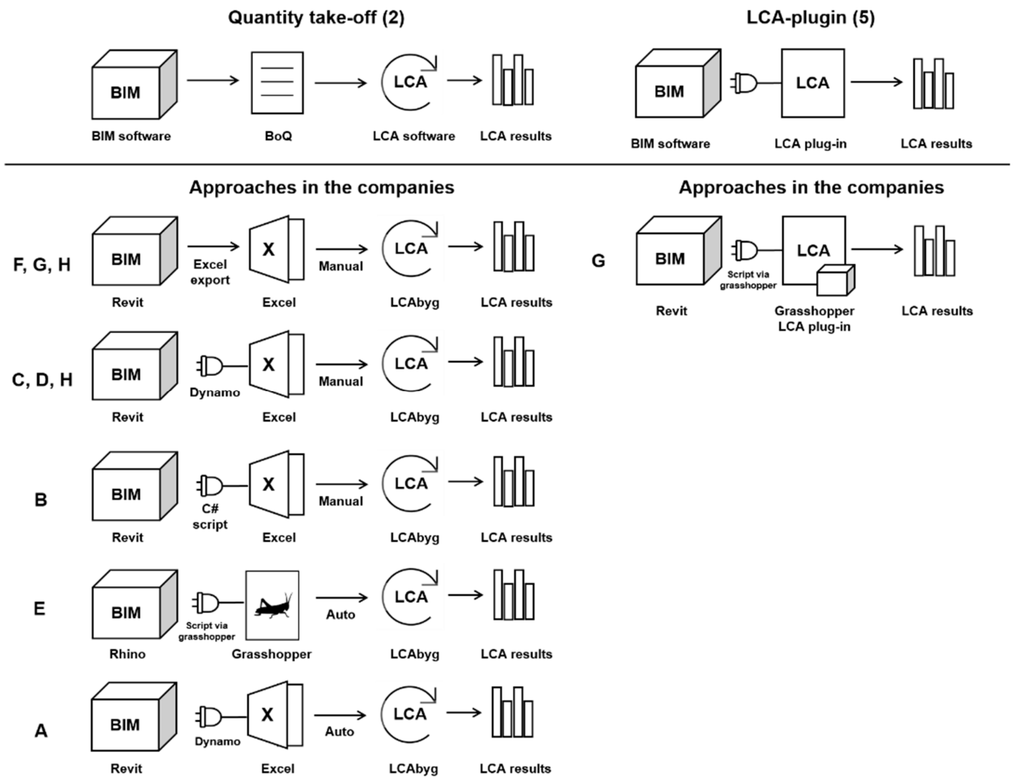

Figure 6. Detailing of BIM–LCA approaches used in the companies.

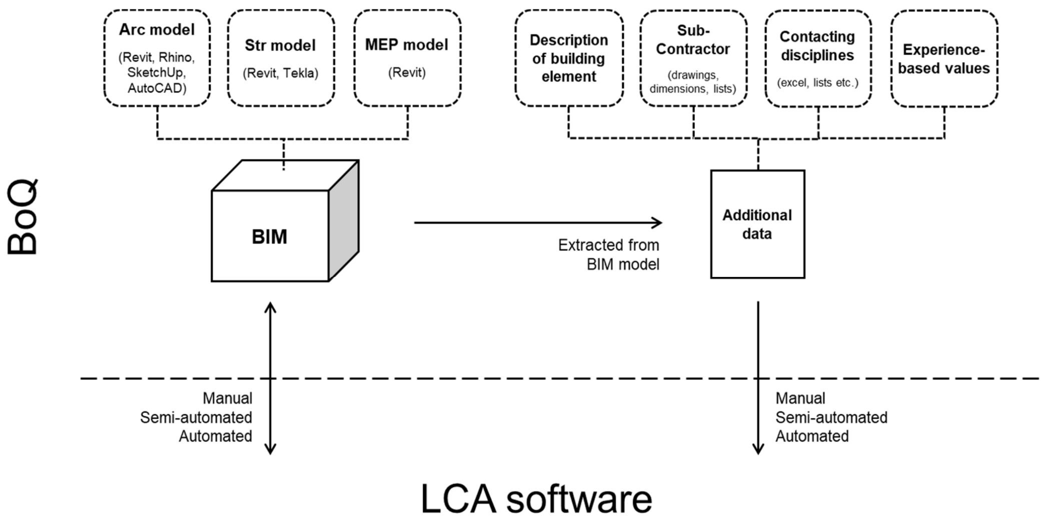

Figure 7. Data sources used in the companies.

Different models exist during a project, and this is reflected in their use within the companies. In general, all the companies mention Rhino as a tool that is used in early design stages, where Sketchup and AutoCAD is also mentioned in a couple of the companies. The Rhino models are in some cases used for the LCA as illustrated in Figure 6. In the more detailed stages, all companies use Revit. They describe Revit as almost an industry standard when modelling in the project design stage. The companies work with different discipline-oriented models in Revit: an architectural model, structural model, and mechanical, electrical, and plumbing (MEP) models. All companies use the architect model for the LCA, but only two companies mention that they extract the data from the structural model and the MEP models to perform the LCA, and only in the detailed design stage.

To supplement data, and to fill the data-gap from only using the architectural model, the companies mentioned additional data sources. These include descriptions of building elements, data from sub-contractors, and gathering data from the discipline groups such as the structural or HVAC (heating, ventilation, and air conditioning) engineer. Two companies also mentioned the use of experience-based values from earlier projects or the literature to supplement in earlier stages, when data is not available. The use of descriptions of building elements is mentioned by company B, C, and H for LCA in the early design stage, when information in the model is limited or when it is not defined in the BIM. Element details are gathered from the supplier, for example the concrete element supplier, because they have more detailed information on the elements. If information or data are missing in the BIM model, the companies contact the discipline groups to collect the missing information. An example of this is company A, who collects information by providing the different discipline groups with Excel sheets, where they can fill in the data.

4.3. Challenges in BIM–LCA

During the interviews, the individual companies were asked which challenges the company faces when making LCA from the building models. The challenges are listed in Table 3, where they are separated into eight overall challenges.

Table 3. Challenges of BIM–LCA mentioned by the companies.

Challenges	Comments
Lack of building-model management for a collaborative process	• Those who need information from the model (e.g., quantities of materials) are not the ones who model it (A, F, C); • Modelling starts very late in some projects, especially the structural model (G); • The consulting engineer may not design the ventilation system themself, but puts it out to tender. Thus, they don't have the model (G, F); • Contractual issues means that they cannot edit in, e.g., the architectural model (D); • No minimum demands for LOD on material information exists (A); • No common understanding or standard for extraction of quantities (F); • Challenging to motivate other actors to include materials in the Revit model, when it takes long, and gives no value to the one who does the modelling (F); • Lack of responsibility of the quantities in models (A);
Workflow errors	• Human error when manually typing into LCAtool from 8–10 different Revit schedules (F); • Extracting quantities from Revit is a black box, where it is not possible to see if anything is missing (F); • Difficult to check the models for errors, when someone else has made the model (A); • Paint areas are wrong, if the suspended ceiling is not accounted for (A);

Table 3. *Cont.*

Challenges	Comments
Lack of data availability and quality in models	• The data in the models are not good enough to form a basis for a good BIM–LCA integration (A); • Issues with extracting correct quantities from the models (F), specifically volumes (D); • The models are modeled incorrectly in terms of extracting quantities, although the graphical representation of the model looks correct (F); • Quantities will always be incorrect to some degree (C); • 10–15% of the model is not modelled correctly (G); • Quality of the modelled elements vary (G); • MEP model is not used for the LCA because it is not good enough. They collect the quantities on a list from the engineer (G); • Structural model from the consulting engineer is not as good as getting information from element supplier (G); • Not all materials are modeled in the model, e.g., steel in the plaster wall (B); • Detailing is not very high in the Revit model, e.g., they don't model reinforcement or holes in slaps (G); • Detailing varies (C); • Not all data are available in the model and likely never will be (C); • Often there is no structural or MEP building model (more often in office buildings, as they have higher demands) (G); • Information is not in the Revit model, only geometry (E); • Materials are not in the models (D, A);
Modeling errors	• Delta beams, piping, etc. are drawn as solids, resulting in the wrong volume (A); • No reinforcement in concrete elements (A); • Errors in model, e.g., internal walls are modelled as external walls (H, C) or as wall instead of foundation (A); • Some elements are modelled doubled, because several disciplines have modelled them (e.g., architectural and structural models both include structural elements). There is a risk of double counting (A, F, G); • Wrong dimensions of elements (A); • Columns drawn through slaps, giving the wrong volume (A); • Windows drawn as curtain walls (A);
Variations in the structure of models	• The structure in the models varies (B, D), and the model they get from the architect is structured differently each time (C); • The structure of the objects in the models varies (B), e.g., variation in the construction of the floor; with or without deck, etc. In the early design stage the objects are modelled as generic elements, while in the detailed design stage the building elements are modelled with all functional layers, e.g., ceiling, floor; • Modelling is different in other nations (G);
Data exchange and matching model-data with LCIA data	• Quantity outputs units from models are sometimes difficult to use for LCA, e.g., "pieces" of stairs (G); • Matching quantities with LCIA data from LCAbyg (C); • It is a challenge to create generic plugin scripts for all models as they are modeled differently. They always need to adjust the VPL/script (D); • Difficult to predict the future and thereby develop tools or a workflow for future processes (A); • Oversimplified or too user-friendly tools (F); • Issues with stability and/or workflow of different VPL (A, B, C, F, H);
Manual workflow and large models	• Time consuming with manual BIM–LCA workflow (F, G); • Extracting quantities/checking data is the most time-consuming process (D, A); • The large number of elements in a model makes it a time-consuming process (A); • Too much information in the models can make them slow to work with (D).

Some of the most commonly mentioned challenges are the lack of data availability and quality in the models used to establish the BoQ. An architect mentions that the models have not been made for the purpose of quantity extraction, but with other aspects in mind, thus the quantity take-off is wrong. It is also mentioned that some of the discipline models, such as structural and MEP, often do not exist, or are not reliable for quantity take-off. Further, the detailing varies, but some materials are simply not included in the model, such as reinforcement, and steel in plaster walls. Several mentioned that it is not likely that quantities will ever be completely correct in the model. Model errors are listed as a separate challenge in Table 3, however, they only contribute to the lack of quality in the models.

Furthermore, the structure and classification of the models can vary a lot, which can influence the data exchange. For instance, if a plugin expects a certain structure, but the model doesn't have this structure. When matching the BoQ to LCIA data, a common challenge mentioned is matching the units, as they may not align. It is also a source of human error, if the match is done manually. Some mention that the manual processes are time-consuming. This also includes manually checking the quantity take-off, due to the above-mentioned lack of quality.

To some degree, these challenges are a result of the lack of management or standardization of the models in relation to LCA, where some mention the lack of method for extraction of quantities, requirements for input of material information, and good-quality models at the time that they need them for the LCA. Further, those who make the LCA are often not the ones who make the building models. Therefore there is a lack of incentive for modeling for quantity take-off, or a lack of responsibility of the quantities in the model which is needed in this collaborative modelling work.

4.4. User-Perspective on Integration and Response to Prototype

The informants were asked about features for the integration process that they found important, and afterward they were presented with the prototype from Section 2.5 and provided feedback. Both of these results are shown in Table 4. In terms of important features for the BIM–LCA, one of the informants said that the integration should help solve the data issues from BIM. This refers back to the challenges, mentioned in Section 4.3, where several companies questioned the quality of their models, and their completeness. The 3D view was mentioned as a positive feature in connection to transparency of data from the model. Due to the quality of the models, they need to check the quantities, thus the 3D view will help them understand the origin and calculation of quantities, and to see if there are collisions of elements. The 3D view was also mentioned in relation to visualization, where several companies suggested it and found it to be a positive feature in the prototype. In general, six out of the eight companies mentioned the positive in a visual interface for the BIM–LCA integration. They mention its positive effects on communication and discussing results with different actors of the projects, especially at early design stages. Two engineering companies stated that they do not necessarily need a 3D view, as they were worried that the integration process would take longer. In terms of ease-of-use, some worried that the general workflow in larger models might be complex, if they need to review and match all this data with LCIA-data. However, some said that the grouping and filtering of elements can be used to manage the data.

Automation was another theme several of the companies found important. One of the informants mentioned that the models will likely always be wrong, but they still see potential in automating 80–90% of the process. Another informant mentions that automation is valuable, because humans make mistakes, and human mistakes are much harder to find. Automation also has relevance in terms of efficiency, where they currently spend many hours extracting quantities and go through several steps to make the LCA. To make automation easier, one informant suggests to "enrich" the BIM with information that can automatically match to the LCIA data. When presented with the prototype, one found it positive that the IDs from the IFC would make it easy to update the model, while another mentioned the lack of dynamic or parametric features.

Table 4. Important aspects of the BIM–LCA integration process mentioned by the companies, and their comments on the prototype.

Important Properties for Integration Process		Comments on Prototype
Ease of use (G, H)	• Everyone should be able to use it. It should be simple (G); • Help solve the issues in data from BIM (H);	Cons: • In a building model, they have 300 different Revit "families". This might be too much work/too complex to work with in the prototype. (A, B, F); • Worried that the tool cannot handle larger models (that the program might crash) (D, G);
Visual interface (A, B, C, D, E, H)	• Important for early design stages (D, E); • Interface with 3D-model (A, E, H,); • To communicate and discuss results of LCA with other actors (B, C);	Pros • 3D interface (C, D, E, F, H); • Communicate result to client (B); • That you see a 3D view of the actual building, you are working on, not just a generic model. (F); • You can see the objects you have matched to LCIA data vs. those you haven't yet (F); Cons: • It might be faster to manage the data without the 3D view. They don't always need a 3D view, if it takes more time (B, C);
Evaluation of design solutions (B, C, G, E, H)	• Show where to focus the optimization, e.g., the largest impacts (H); • Comparison of building elements and materials (B); • Comparison with their own or certification references/benchmarks for buildings (B, H); • Important for early design stages (E);	Pros: • Comparison of design solutions (B);
Transparency of data from the building model (A, B, C, H, F)	• They need to assess the quality of the model, therefore, they need to see how BoQ is connected to the information from the building model (H); • The models will likely always be wrong, so they have to check it (A, B); • Possible to see where there are changes or new objects, when you update the model (C); • Highlight obvious errors, e.g., the building being much heavier than similar building. (F); • 3D visualization with names and thickness of elements (H);	Pros: • Quality assurance of data, especially when elements can be filtered/grouped together (G); • See all the building elements in 3D view (H); • Easy to understand the origin of quantities with 3D view (D, A); • You can see how areas are calculated due to the 3D view (C); • Quantities are also calculated within the tool, not just quantities from Revit (F); • You can more easily see if you are missing element/materials (F); • Collision control (F); Cons: • Too complex in larger models to do quality control (B);
Precision and completeness of BoQ data (B, D, E, F)	• The LCA should have large detailing already at early stages. Therefore you should be informed of missing elements, e.g., ventilations systems (F); • Quantities from the building model should be correct (D); • Important at later stages (D, E);	

Table 4. *Cont.*

Important Properties for Integration Process		Comments on Prototype
Quick/automation (B, C, D, H, F)	• Currently, there are too many steps before the final LCA can be made (H); • They spend many hours extracting quantities (B); • Retrieve quantities from the model and update them automatically when the model changes (B); • The matching of BoQ with LCIA should be remembered when the model is updated (B); • If 80–90% of the process in the future will be automated, it will be a great help (B); • To make an automatic match of quantities with LCIA data, LCIA should be included in Revit/IFC (B); • Automation of the processes is a good idea, because human errors are difficult to find (F); • Important for early design stages (D);	Pros: • Easy to update the model, due to ID's when using IFC (F); • The prototype tool contains the library used in the Danish tool, LCAbyg (H); Cons: • Not dynamic or parametric (E); • If the architect deletes a wall and draws a new wall, it will have a new ID, and then you cannot as easily update the LCA anymore (C);
Flexible workflow in terms of data sources (A, C, E, F, H)	• Import of IFC and Revit, as this is what is most commonly used in the industry (H); • Not certain that Revit is what we use in the future, therefore more file formats should be possible to use (F);	Pros: • Can possibly solve the issue with the uses of different building model tools in the industry (H) • Neutral file format (H); • The possibility to use areas as quantities and match with LCIA-data for predefined elements, as an alternative to specific quantities such as m3, kg. (D); • Choose what data, they use from the models, because they know that some information is not correct (A); • Possibility to overwrite and adjust quantities and structure from the building model in the LCA (G); Cons: • They prefer that it is made specifically for Revit, because they mainly use Revit (D); • They might prefer exchange via files such as 3DM or MWD as it might be faster than IFC (C);

Five companies also find the flexibility of data sources important. One mentions that IFC and Revit are the most commonly used data sources in the industry, and thus should be supported in a tool for BIM–LCA. Another mentioned that it is not certain that Revit will be the main tool in the future, therefore other data sources should be supported. When presented with the prototype, some found the use of a neutral file format positive, while others preferred to focus on Revit or use different file formats than IFC and OBJ. Some had a general experience of "loosing" their data when they had previously used IFC in their work. In the prototype, some found the flexibility positive; in terms of choosing only the data that they find relevant from the model, as well as the type of quantities relevant to the stage of the project, e.g., choosing areas instead of kg and m3 for early design.

Evaluation of design solutions was also important to consider in BIM–LCA for several of the companies, in order to get instant feedback on design solutions and whether or not they meet certain benchmarks. Four of the companies also mentioned that precision of data is important, including completeness of data already in the early stages, such as by including installations. Referring back to the challenges in Section 4.3, this information may not be available in the model and thus have to be added in the BIM–LCA process.

5. Discussion

5.1. Data Management

The companies interviewed for this study only used the model to store data related to extracting the BoQ. However, storing more LCA-related data in the model can reduce human error, support automation, and facilitate better use of the models across the life cycle of the building [33]. Moreover, it complies with the concepts surrounding BIM, which focus on information sharing and collaboration across the building life cycle. However, the workflow for this "enriched BIM" first needs to be established [33] and may vary depending on the goal and context of the LCA, as well as the structure used in the model. Further, if the model includes environmental data, it can be a challenge to manage if it is up-to-date [63]. Inclusion of environmental information in the BIM and using the IFC-viewer workflow has been tested in the literature before, with more focus on the later stages [59]. However, the process is associated with practical challenges, because even though IFC can contain this information, some properties, attributes, and entities are not available in industry BIM [59,64]. Further, the IFC schema still needs to be improved to allow information for a full LCA [33].

Despite only using BoQ data from the model, the companies are met with challenges related to the quality of the model and many use supplementary sources to complete or detail the BoQ. Poor design of models for LCA and life cycle performance has been recognized in the previous literature [4,35], and is confirmed and specified in this study. While future legislation demands for LCA might improve the collaboration related to quantities in the models, several companies expressed that it is not realistic that the models become perfect in terms of quantity extraction. An issue therefore lies both in how the BoQ data from the models can be improved, and what expectations regarding the precision of BoQ is expected from the building LCA at different stages. Automation could be a possible solution to improve upon the data quality, such as automatically adding reinforcement in concrete elements. However, automatic or semi-automatic approaches can also be imprecise and reduce transparency in the process. In terms of the expected precision of the LCA, the practitioners will likely need clear guidance regarding this aspect in relation to benchmarking their building.

In early design stages other strategies can be used, such as matching quantities with predefined elements, as suggested in this article as well as in previous studies [2,21,24,37,49].

5.2. Tool for BIM–LCA

The prototype for the Danish context includes the visual interface in correlation with conducting the building LCA. The companies were generally positive towards the 3D view in the prototype for both transparency of data and visualization of results. Some of the companies were also working towards their own plugin approach with 3D view, especially for early design stages. In the development of the prototype, it could be relevant to be inspired by the plugin–workflow, for instance by allowing the user to modify the geometry in the prototype to achieve the same dynamic effects, and test different designs. A challenge in the plugin–solution is the dependency on one specific building model tool. The companies from this study mainly use Revit, and some therefore preferred a direct data-exchange for this software. However, for the early design stages, it is more common to use a variety of tools, and some companies also expressed the positive in using neutral file formats in order to support a variety of modelling tools. It is likely that some companies will want to optimize internal processes, and thus develop their own tools, while others will require ready-to-use software. Software providers and policy-makers should therefore allow for different workflows, and provide a clear description of method.

5.3. Limitations

While the interviews can give detailed insight into workflow, challenges, and demands for BIM–LCA in industry practice, it should be noted that this study is a qualitative study with a limited sample size. Thus the results from the study represent the experience in eight different companies in Denmark. The companies cover a large share of the Danish AEC industry due to the large size of some of the included companies. The companies are of varying size, however, small and one-man businesses are not represented in the interviews, because it was assumed that they would have limited experience in the subject. Omitting the small companies can potentially have an influence on the informant's feedback on the prototype. This is because small companies can be more dependent on ready-to-use tools, such as the prototype, because they have less resources to develop their own integration of BIM–LCA. The prototype facilitates an integration process where all models, independent from which software the model is created in and how it is structured, can be used for BIM–LCA. Future development of the prototype should therefore include considerations of smaller companies.

6. Conclusions

This paper has provided insight into industry practice of BIM–LCA through eight in-depth interviews with consulting and contracting firms. All the companies use a quantity take-off approach for the BIM–LCA and some have recently made, or are currently developing, plug-in solutions. Nevertheless, due to the lack of quality in the models, it is often necessary to supplement the model-data with data from other sources, such as element descriptions and contacting engineering disciplines and subcontractors. The lack of quality and variations in modeling are dominant challenges mentioned by the companies. Many of these issues points back to a management of the models, which is not optimal for quantity take-off. In the future, the quality of the models may improve due to legislations in, e.g., LCA, however, some degree of inaccuracy should always be expected, especially in early design stages. For the integration of BIM–LCA it should therefore be considered how the inaccuracy is dealt with. Moreover, to which degree automation can be incorporated in the process. For legislation and benchmarking, the level of detail expected for the LCA should be clearly defined.

The informants also provided needs for BIM–LCA and evaluated a prototype for BIM–LCA in a Danish context with the use of open neutral file formats and a 3D view. The companies considered several aspects important in BIM–LCA, including visual interface, transparency of data, automation, flexibility of data sources, and easy access to evaluation of design solutions. Many considered the 3D view in the prototype valuable for transparency and communication, but some questioned its efficiency and use for their larger models. The prototype uses open and neutral file formats such as IFC and OBJ for the data exchange, which garnered mixed responses from the companies. Some valued the flexibility it can provide in terms of using models from different software, while others preferred optimizing the direct data exchange to their predominantly used tool, Revit. Companies will have different resources and goals, and thus different needs in relation to workflow for BIM–LCA. Specifically smaller companies will likely benefit from ready-to-use solutions such as the prototype, because there are no requirements to the structure of the model, or the software used for modeling. A strategy for software developers and decision-makers can therefore be to allow for different workflows, but provide transparency of results and clear descriptions of method.

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Glossary

AEC	Architecture: Engineering and Construction
API	Application Programming Interface
BIM	Building Information Modeling
BoQ	Bill of Quantities
DGNB	Deutsche Gesellschaft fur Nachhaltiges Bauen
EPD	Environmental Product Declaration
FM	Facility Management
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IFC	Industry Foundation Class
JSON	JavaScript Object Notation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LOD	Level of Development
MEP	Mechanical, electrical and plumbing
VPL	Visual Programming Language

References

1. United Nations Environment Programme. *2020 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector*; United Nations Environment Programme: Nairobi, Kenya, 2020.
2. Kanafani, K.; Zimmermann, R.K.; Rasmussen, F.N.; Birgisdóttir, H. Learnings from developing a context-specific LCA tool for buildings—The case of lcabyg 4. *Sustainability* **2021**, *13*, 1508. [CrossRef]
3. Frischknecht, R.; Balouktsi, M.; Lützkendorf, T.; Aumann, A.; Birgisdottir, H.; Ruse, E.G.; Hollberg, A.; Kuittinen, M.; Lavagna, M.; Lupišek, A.; et al. Environmental benchmarks for buildings: Needs, challenges and solutions—71st LCA forum, Swiss Federal Institute of Technology, Zürich, 18 June 2019. *Int. J. Life Cycle Assess.* **2019**, *24*, 2272–2280. [CrossRef]
4. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of bim-based LCA method to buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]
5. Rasmussen, F.N.; Malmqvist, T.; Birgisdóttir, H. Drivers, barriers and development needs for LCA in the Nordic building sector—A survey among professionals. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*. [CrossRef]
6. Balouktsi, M.; Lützkendorf, T.; Röck, M.; Passer, A.; Reisinger, T.; Frischknecht, R. Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*. [CrossRef]
7. Obrecht, T.P.; Röck, M.; Hoxha, E.; Passer, A. BIM and LCA Integration: A Systematic Literature Review. *Sustainability* **2020**, *12*, 5534. [CrossRef]
8. Wastiels, L.; Decuypere, R. Identification and comparison of LCA-BIM integration strategies. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*. [CrossRef]
9. Chastas, P.; Theodosiou, T.; Kontoleon, K.J.; Bikas, D. Normalising and assessing carbon emissions in the building sector: A review on the embodied CO_2 emissions of residential buildings. *Build. Environ.* **2018**, *130*, 212–226. [CrossRef]
10. Russell-Smith, S.V.; Lepech, M.D.; Fruchter, R.; Littman, A. Impact of progressive sustainable target value assessment on building design decisions. *Build. Environ.* **2015**, *85*, 52–60. [CrossRef]
11. Rasmussen, F.N.; Ganassali, S.; Zimmermann, R.K.; Birgisdóttir, H. LCA benchmarks for residential buildings in Northern Italy and Denmark. *Build. Res. Inf.* **2019**, *47*, 833–849. [CrossRef]
12. Blengini, G.A.; Di Carlo, T. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy Build.* **2010**, *42*, 869–880. [CrossRef]

13. Röck, M.; Ruschi Mendes Saade, M.; Balouktsi, M.; Nygaard, F.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T. Embodied GHG emissions of buildings—The hidden challenge for e ff ective climate change mitigation. *Appl. Energy* **2019**, *258*, 114107. [CrossRef]
14. Moncaster, A.M.; Rasmussen, F.N.; Malmqvist, T.; Houlihan Wiberg, A.; Birgisdottir, H. Widening understanding of low embodied impact buildings: Results and recommendations from 80 multi-national quantitative and qualitative case studies. *J. Clean. Prod.* **2019**, *235*, 378–393. [CrossRef]
15. International Organization for Standardization. *ISO 14040: Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO: Geneva, Switzerland, 2006.
16. International Organization for Standardization. *ISO 14044: Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO: Geneva, Switzerland, 2006.
17. European Committee for Standardization. *EN 15978: Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method*; CEN: Brussels, Belgium, 2011.
18. Lützkendorf, T. Assessing the environmental performance of buildings: Trends, lessons and tensions. *Build. Res. Inf.* **2017**, *3218*, 1–21. [CrossRef]
19. Zimmermann, R.K.; Skjelmose, O.; Jensen, K.G.; Jensen, K.K.; Birgisdottir, H. Categorizing Building Certification Systems According to the Definition of Sustainable Building. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*. [CrossRef]
20. The government (the Social Democratic Party); Venstre; Dansk Folkeparti; the Socialist People's Party; Radikale Venstre; Enhedslisten; the Conservative People's Party and the Alternative. *National Strategi for Bæredygtigt Byggeri*; The Danish parliament: Copenhagen, Denmark, 2021; pp. 1–8.
21. Meex, E.; Hollberg, A.; Knapen, E.; Hildebrand, L.; Verbeeck, G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Build. Environ.* **2018**, *133*, 228–236. [CrossRef]
22. Lamé, G.; Leroy, Y.; Yannou, B. Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs. *J. Clean. Prod.* **2017**, *148*, 60–72. [CrossRef]
23. Saunders, C.L.; Landis, A.E.; Mecca, L.P.; Jones, A.K.; Schaefer, L.A.; Bilec, M.M. Analyzing the practice of life cycle assessment: Focus on the building sector Saunders et al. Analyzing the practice of life cycle assessment. *J. Ind. Ecol.* **2013**, *17*, 777–788. [CrossRef]
24. Marsh, R.; Rasmussen, F.N.; Birgisdottir, H. *Embodied Carbon Tools for Architects and Clients Early in the Design Process*; Pomponi, F.A., Moncaster, C.D.W., Eds.; Springer: Berlin/Heidelberg, Germany, 2018; ISBN 978-3-319-72796-7.
25. Basbagill, J.; Flager, F.; Lepech, M.; Fischer, M. Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Build. Environ.* **2013**, *60*, 81–92. [CrossRef]
26. John, V. Derivation of Reliable Simplification Strategies for the Comparative LCA of Individual and "Typical" Newly Built Swiss Apartment Buildings. Ph.D. Thesis, ETH, Zürich, Switzerland, 2012.
27. The European Parliament and the Council of the European Union. Directive 2014/24/EU of The European Parliament and of The Council of 26 February 2014 on Public Procurement and Repealing Directive 2004/18/EC (Text with EEA Relevance). *Off. J. Eur. Union* **2014**, *94*, 65–242.
28. Erhvervsministeriet. *Udbudsloven*; Erhvervsministeriet: Copenhagen, Denmark, 2015; pp. 1–9.
29. Transport- og Boligministeriet. *Bekendtgørelse om Anvendelse af Informations- og Kommunikationsteknologi (IKT) i Offentligt Byggeri*; Transport- og Boligministeriet: Copenhagen, Denmark, 2013.
30. Laakso, M.; Kiviniemi, A. The IFC standard—A review of history, development, and standardization. *Electron. J. Inf. Technol. Constr.* **2012**, *17*, 134–161.
31. Theißen, S.; Höper, J.; Drzymalla, J.; Wimmer, R.; Markova, S.; Meins-Becker, A.; Lambertz, M. Using Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA. *Sustainability* **2020**, *12*, 5644. [CrossRef]
32. Horn, R.; Ebertshäuser, S.; Di Bari, R.; Jorgji, O.; Traunspurger, R.; von Both, P. The BIM2LCA approach: An industry foundation classes (IFC)-based interface to integrate life cycle assessment in integral planning. *Sustainability* **2020**, *12*, 6558. [CrossRef]
33. Santos, R.; Costa, A.A.; Silvestre, J.D.; Pyl, L. Integration of LCA and LCC analysis within a BIM-based environment. *Autom. Constr.* **2019**, *103*, 127–149. [CrossRef]
34. Figl, H.; Ilg, M.; Battisti, K. 6D BIM-Terminal: Missing Link for the design of CO-neutral buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*. [CrossRef]
35. Saridaki, M.; Psarra, M.; Haugbølle, K. Implementing life-cycle costing: Data integration between design models and cost calculations. *J. Inf. Technol. Constr.* **2019**, *24*, 14–32.
36. Kiss, B.; Röck, M.; Passer, A.; Szalay, Z. A cross-platform modular framework for building Life Cycle Assessment. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*. [CrossRef]
37. Röck, M.; Hollberg, A.; Habert, G.; Passer, A. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
38. Tsikos, M.; Negendahl, K. Sustainable Design with Respect to LCA Using Parametric Design and BIM Tools. In Proceedings of the World Sustainable Built Environment Conference 2017, Wan Chai, Hong Kong, 5–7 June 2017.
39. CSTB EveBIM. Available online: https://www.evebim.fr/ (accessed on 23 April 2021).
40. Cavalliere, C.; Dell'Osso, G.R.; Pierucci, A.; Iannone, F. Life cycle assessment data structure for building information modelling. *J. Clean. Prod.* **2018**, *199*, 193–204. [CrossRef]

41. Mora, T.D.; Bolzonello, E.; Cavalliere, C.; Peron, F. Key parameters featuring bim-lca integration in buildings: A practical review of the current trends. *Sustainability* **2020**, *12*, 7182. [CrossRef]
42. Antón, L.Á.; Díaz, J. Integration of life cycle assessment in a BIM environment. *Procedia Eng.* **2014**, *85*, 26–32. [CrossRef]
43. Díaz, J.; Antön, L.Á. Sustainable construction approach through integration of LCA and BIM tools. In Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering, Orlando, FL, USA, 23–25 June 2014; pp. 283–290. [CrossRef]
44. Buildingsmart. Available online: https://www.buildingsmart.org/ (accessed on 11 March 2021).
45. Toth, B.; Janssen, P.; Stouffs, R.; Chaszar, A.; Boeykens, S. Custom digital workflows: A new framework for design analysis integration. *Int. J. Archit. Comput.* **2012**, *10*, 481–500. [CrossRef]
46. Negendahl, K. Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Autom. Constr.* **2015**, *54*, 39–53. [CrossRef]
47. Grasshopper. Available online: https://www.grasshopper3d.com/ (accessed on 15 March 2021).
48. Dynamo. Available online: https://dynamobim.org/ (accessed on 15 March 2021).
49. Cavalliere, C.; Habert, G.; Dell'Osso, G.R.; Hollberg, A. Continuous BIM-based assessment of embodied environmental impacts throughout the design process. *J. Clean. Prod.* **2019**, *211*, 941–952. [CrossRef]
50. Dupuis, M.; April, A.; Lesage, P.; Forgues, D. Method to Enable LCA Analysis through Each Level of Development of a BIM Model. *Procedia Eng.* **2017**, *196*, 857–863. [CrossRef]
51. Durão, V.; Costa, A.A.; Silvestre, J.D.; Mateus, R.; De Brito, J. Integration of environmental life cycle information in BIM objects according with the level of development. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*. [CrossRef]
52. Durão, V.; Costa, A.A.; Silvestre, J.D.; Mateus, R.; Santos, R.; Brito, J. De Current Opportunities and Challenges in the Incorporation of the LCA Method in BIM. *Open Constr. Build. Technol. J.* **2020**, *14*, 336–349. [CrossRef]
53. Frivillig Bæredygtighedsklasse. Available online: https://baeredygtighedsklasse.dk/ (accessed on 16 March 2021).
54. Green Building Council Denmark. Available online: https://www.dk-gbc.dk/english/ (accessed on 16 March 2021).
55. Ökobaudat. Available online: https://www.oekobaudat.de/ (accessed on 16 March 2021).
56. Birgisdottir, H.; Rasmussen, F.N. Development of LCAbyg: A national Life Cycle Assessment tool for buildings in Denmark. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*. [CrossRef]
57. Kanafani, K.; Zimmermann, R.K.; Rasmussen, F.N.; Birgisdóttir, H. Early Design Stage Building LCA Using the LCAbyg Tool: New Strategies for Bridging the Data Gap. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*. [CrossRef]
58. Zimmermann, R.K.; Kanafani, K.; Nygaard Rasmussen, F.; Birgisdóttir, H. Early Design Stage Building LCA using the LCAbyg tool: Comparing Cases for Early Stage and Detailed LCA Approaches. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*. [CrossRef]
59. Theißen, S.; Höper, J.; Wimmer, R.; Zibell, M.; Meins-Becker, A.; Rössig, S.; Goitowski, S.; Lambertz, M. BIM integrated automation of whole building life cycle assessment using German LCA data base ÖKOBAUDAT and Industry Foundation Classes. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *588*. [CrossRef]
60. Ligurgo, V.; Philippette, T.; Fastrez, P.; Collard, A.S.; Jacques, J. A Method Combining Deductive and Inductive Principles to Define Work-Related Digital Media Literacy Competences. *Commun. Comput. Inf. Sci.* **2018**, *810*, 245–254. [CrossRef]
61. Realdania. *Byggeriets Nøgletal*; Realdania: Copenhagen, Denmark, 2016.
62. Danske Arkitektvirksomheder. Available online: https://www.danskeark.dk/content/tal-analyser (accessed on 16 March 2021).
63. Röck, M.; Passer, A.; Ramon, D.; Allacker, K. The coupling of BIM and LCA—Challenges identified through case study implementation. In *Life Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision*; Taylor & Francis Group: London, UK, 2019; pp. 841–846.
64. Petrova, E.A.; Romanska, I.; Stamenlov, M.; Svidt, K.; Jensen, R.L. Development of an Information Delivery Manual for Early Stage BIM-based Energy Performance Assessment and Code Compliance as a Part of DGNB Pre-certification. In Proceedings of the 15th IBPSA Conference: Building Simulation 2017, San Francisco, CA, USA, 7–9 August 2017. [CrossRef]

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