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Eirik Resch

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Thesis for the Degree of
Philosophiae Doctor
Faculty of Architecture and Design
Department of Architecture and Technology

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Assessment of GHG emissions from materials during building design

Methods for improved reliability and quality

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Preface

This doctoral dissertation is submitted for the joint degree of *Philosophiae Doctor* at the Norwegian University of Science and Technology (NTNU) and the Technical University of Denmark (DTU). The work was funded by NTNU. The research was conducted at NTNU and partially at DTU, under the supervision of professors Inger Andresen (NTNU), Helge Brattebø (NTNU), and Henrik Madsen (DTU) whom I would like to thank for their knowledgeable guidance, contributions, and full support throughout the process.

A total of 5 peer-reviewed scientific articles are the core of the dissertation. Four are published in international peer-reviewed journals, and one in an international peer-reviewed conference proceeding. In addition, four more articles are related to the work and are appended as supplementary papers.

Part A of the thesis connects the published works, places them into context, and conveys the essential contributions of the conducted research as a combined work. Part B contains the main articles in their original format. Part C contains the supplementary articles.

I am thankful for being part of a society that values knowledge generation and gave me the opportunity to freely conduct research on this important topic. It is hoped that the proposed methodologies and findings will contribute to transitioning the building industry into a positive force for global climate mitigation. To do so, immediate and continued progressive change is needed by all actors.

I would like to deeply thank all the people around me for their truly priceless continued support on the personal as well as the professional level, and for making the Ph.D. endeavor a very enjoyable time in my life; my family, friends, and all the other humans I crossed path with.

Abstract

Construction materials in buildings contribute significantly to climate change. Globally, nations have committed to drastic reductions of greenhouse gases (GHG), among them Norway which has committed to 50-55% reduction by 2030 and 90-95% by 2050. Building material use and the related construction activities are among the areas that must drastically reduce impacts to achieve those goals.

Such mitigation efforts are limited by current assessment methods. Improved methods for estimation of these climate change impacts are needed in the early project phases to improve the design and planning. Methods for benchmarking results against reference values are needed both to improve design and for effective regulation. Quantification methods are also immature. Material use in buildings affects the climate over centuries, however, temporal aspects are often ignored in Life Cycle Assessment (LCA). Results too often promise uncontested precision of impacts occurring far into the future. Additionally, the validity of building LCAs is being questioned over inadequate scope and inventory. The goal of this thesis is to contribute with methods addressing those limitations, to enable effective reduction of building materials' contribution to climate change.

The body of research on the impacts of individual buildings is growing, but the results and data remain inaccessible and incomparable due to insufficient reported information, differences in system boundaries, assumptions, methods, and data used. This inhibits further utilization of results in statistical applications and makes interpretation and validation of results difficult. A database of empirical material use and emission data from building LCA case studies was developed to mitigate these challenges, providing a framework for impact assessment in the planning and design phases. Systematizing and storing relevant information for these case studies in a compatible format enables comparison and harmonization of results across system boundaries and assumptions, improves the transparency and reproducibility of the assessments, and makes utilization of the results in statistical applications possible.

A dynamic LCA method for material use in buildings was developed. It addresses uncertainty and temporal effects arising from the long lifetime of buildings. In particular, novel solutions for accounting for delayed emissions and future emission reductions due to technological improvements are proposed. Climate change effects of material use in construction, operation, and end-of-life phases are estimated, from production, transport, construction-waste incineration, biogenic carbon-sequestration, and cement carbonation. The importance of choosing a normative time horizon for the estimated climate change impacts is emphasized.

A method was also developed for evaluating and visualizing the climate change impacts of material use by linking the material inventory data with the aggregated results through a set of metrics for a building and its subparts. These subpart metrics can be compared to the rest of the building and to results from other buildings, and statistical benchmarks can be established. This intermediate calculation step simultaneously serves as a breakdown of the results and an aggregation of the building's inventory data. The subpart metrics lay the foundation for applications throughout the project phases by enabling combined use of case-specific data and statistical data.

Uncertainty is estimated from variation in the dataset, and further, from sampling results while varying assumptions. Parameter influence is assessed with global sensitivity analysis. The time horizon for the impacts, the building lifetime (long time horizons only), and the construction waste parameters are found most sensitive. The method reduces uncertainty of postulated future impacts; an important step in the direction of policy-relevant modeling. It is recommended that building LCA modeling practice adopts the presented methodological concepts to gain trust and policy-relevance.

Case studies are used to demonstrate the methods and to generate statistical results. Rarely have the climate change impacts of material use in buildings been studied by statistical methods, and never this sophisticated. In the early phases of a building project, empirical statistical emission profiles of construction materials can inform mitigation efforts. However, engineers and architects do currently not have sufficient information at disposition. The climate change impacts of building material use in 20 Norwegian case studies of low-emission buildings are made comparable, harmonized, and then studied statistically to find how the impact varies with building types (typology, timber/ concrete), building subparts (building elements, material categories), and time horizon. Anticipated future technological development, and delaying emissions in the coming decades, will together lead to significant reductions of accumulated impacts and thus reduce the importance of future replacements and end-of-life. Results show that global warming policy targets require that the building industry focuses on interventions with short-term effects, such as low immediate impact of materials in the construction phase, as well as demonstrating the importance of reducing impacts from construction waste throughout the building lifetime.

Sammendrag (Norwegian abstract)

Byggematerialer i bygninger bidrar betydelig til klimaendringer. Globalt har nasjoner forpliktet seg til drastiske reduksjoner av klimagasser (GHG), og Norge har forpliktet seg til 50-55% reduksjon innen 2030 og 90-95% innen 2050. Byggematerialbruk og tilhørende byggeaktiviteter er blant områdene som må redusere utslipp drastisk for å nå disse målene.

Slik innsats er begrenset av gjeldende vurderingsmetoder. Forbedrede metoder for estimering av disse klimaendringseffektene er nødvendig i de tidlige prosjektfasene for å forbedre design og planlegging. Metoder for å måle resultater mot referanseverdier er nødvendige både for å forbedre design og for effektiv regulering. Kvantifiseringsmetoder er også umodne. Materialbruk i bygninger påvirker klimaet gjennom århundrer, men tidsavhengige aspekter blir ofte ignorert i Livsløpsvurderinger (LCA). Resultatene lover for ofte for høy presisjon på påvirkninger som skjer langt inn i fremtiden. I tillegg settes spørsmålstegn ved gyldigheten av LCAer av bygninger på grunn av utilstrekkelig omfang og inventar. Målet med denne avhandlingen er å bidra med metoder som adresserer disse begrensningene, for å muliggjøre effektiv reduksjon av byggematerialers bidrag til klimaendringene.

Forskningen på effekten fra enkeltbygninger vokser, men resultatene og dataene forblir utilgjengelige og usammenliknbare på grunn av utilstrekkelig rapportert informasjon, forskjeller i systemgrenser, forutsetninger, metoder og data som er brukt. Dette hemmer videre bruk av resultater i statistiske applikasjoner og vanskeliggjør tolkning og validering av resultatene. En database med empirisk materialbruk og utslippsdata fra LCA-studier av bygninger ble utviklet for å håndtere disse utfordringene, og gir et rammeverk for konsekvensutredning i planleggings- og designfasene. Systematisering og lagring av relevant informasjon for disse casestudiene i et kompatibelt format muliggjør sammenligning og harmonisering av resultater på tvers av systemgrenser og antagelser, forbedrer gjennomsiktigheten og reproduserbarheten av vurderingene, og muliggjør utnyttelse av resultatene i statistiske applikasjoner.

En dynamisk LCA-metode for materialbruk i bygninger ble utviklet. Den adresserer usikkerhet og tidsmessige effekter som oppstår fra bygningers lange levetid. Spesielt foreslås nye løsninger for beregning av forsinkede utslipp og fremtidige utslippsreduksjoner på grunn av teknologiske forbedringer. Effekter av klimaendringer fra materialbruk i byggefase, driftsfase og sluttfase blir estimert for produksjon, transport, forbrenning av byggeavfall, biogen karbonbinding og sementkarbonisering. Viktigheten av å velge en normativ tidshorisont for de estimerte klimaendringseffektene blir understreket.

Det ble også utviklet en metode for å evaluere og visualisere klimaendringseffektene av materialbruk ved å knytte materialinventardataene til de samlede resultatene gjennom et sett av indikatorer for en bygning og dens underdeler. Disse indikatorene kan sammenlignes med resten av bygningen og med resultater fra andre bygninger, og statistiske referanseverdier kan etableres. Dette mellomliggende beregningstrinnet fungerer samtidig som en oppdeling av resultatene og en aggregering av bygningens grunnlagsdata. Underdel-beregningene legger grunnlaget for anvendelser gjennom alle prosjektfasene ved å muliggjøre kombinert bruk av prosjekt-spesifikke data og statistiske data.

Usikkerhet estimeres fra variasjon i datasettet, og videre, fra samplede resultater under varierende antagelser. Parameterinnflytelse blir vurdert med global sensitivitetsanalyse. De mest følsomme parameterene er tidshorisonten for påvirkningene, bygningens levetid (bare lange tidshorisonter) og parametrene for byggeavfall. Metoden reduserer usikkerheten rundt postulerte fremtidige klimakonsekvenser; et viktig skritt i retning av politisk relevant modellering. Det anbefales at LCA-modelleringspraksis for bygninger implementerer de presenterte metodiske konseptene for å øke tillit og politisk relevans.

Casestudier brukes til å demonstrere metodene og for å generere statistiske resultater. Sjelden har klimaendringseffektene av materialbruk i bygninger blitt studert av statistiske metoder, og aldri så sofistikert. I de tidlige fasene av et byggeprosjekt kan empiriske statistiske utslippsprofiler av byggematerialer informere om klimainnsats. Imidlertid har ingeniører og arkitekter foreløpig ikke tilstrekkelig informasjon tilgjengelig. Konsekvensene for klimaendringer fra bruk av byggematerialer i 20 norske casestudier av lavutslippsbygninger ble gjort sammenlignbare, harmoniserte og deretter studert statistisk for å finne ut hvordan virkningen varierer med bygningstyper (typologi, tre/betong), underdeler (bygningsdeler, materialkategorier) og tidshorisont. Forventet fremtidig teknologisk utvikling, og forsinkede utslipp i de kommende tiårene, vil sammen føre til betydelige reduksjoner av akkumulerte påvirkninger og dermed redusere viktigheten av fremtidige utskiftninger og avhendinger. Resultatene viser at målene for global oppvarming krever at byggebransjen fokuserer på inngrep med kortsiktige effekter, som lav umiddelbar påvirkning av materialer i byggefasen, og demonstrerer også viktigheten av å redusere påvirkningen fra byggeavfall gjennom hele bygningens levetid.

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Part A

Dissertation

(*Norwegian: “kappe”*)

Chapter 1

Introduction

Introduction to the topic, the problem statement, and the resulting research questions, followed by an outline of the thesis structure, and an overview of the publications.

Material use in buildings is a major contributor to climate change. Production, transport, and waste treatment of building materials throughout the building lifetime cause vast amounts of greenhouse gas (GHG) emissions every year, and will continue to do so as construction activities are on a steep upward trend [1]. Meanwhile, nations worldwide have committed to drastic reductions of GHGs in the Paris agreement, among them Norway which has committed to 50-55% reduction by 2030 and 90-95% by 2050. Building material use and the related construction activities are among the areas that must drastically reduce impacts to achieve those goals. Despite efforts to harmonize results of building LCAs, large ranges in reported results are still observed [2]. The variation can partly be attributed to differences in building design and construction practices, but much of the variation is due to differences in methodology [3; 4]. The climate change impacts of building material use have not yet been implemented in laws and regulations, nor is it common to have a strong focus on this in construction projects. Although operational energy use is the main culprit of emissions from existing buildings, the indirect emissions related to material use are increasingly important in energy-efficient modern buildings [1; 5; 6; 7]. Moreover, most emissions from material use are concentrated around the time of construction, and to reach the ambitious climate goals set by governments, emission reduction today is therefore of utmost importance. There is a need for methods that allow estimation of climate change impacts from material design in early project phases, and reliable reference values that can be used as benchmarks for new constructions.

1.1 Background and theory

1.1.1 The relevance of embodied emissions in buildings

According to the IPCC, buildings account for 19% of worldwide anthropogenic greenhouse gas (GHG) emissions [8]. This translated to 9.3 GtCO_2 equivalents (8.8 GtCO_2) in 2010, and by mid-century, the energy demand from buildings is projected to approximately double and CO_2 emissions to increase by 50-150%. Emissions from construction activities come *in addition* to these operational energy related emissions [8]. It has been estimated that, by improving resource efficiency in the construction and use of infrastructure and buildings, the EU can influence as much as 42% of its final energy consumption, about 35% of its GHG, and more than 50% of all extracted materials [9].

As explained above, a significant fraction of the climate change impacts of buildings can be attributed to material use and construction processes. These indirect impacts are often called embodied emissions (EE) or embodied carbon, and are associated with various processes relating to material use, including extraction, production, and transportation, as well as the construction process and the deconstruction, recycling, reuse, and disposal of materials at the end-of-life. In buildings built without energy efficiency as a priority, it has been showed that 10-30% of total environmental impacts come from indirect processes [10], while the rest come from operational energy use. In newer buildings where operational energy efficiency has been given high priority, the fraction of embodied material emissions alone can be as much as 75% of total emissions (3–6 kgCO2e/m2/year) as shown by one comparative study [5], and 87% (6-21 kgCO2e/m2/year) as shown by another [6] study. This is due to lower operational energy consumption and different material use than traditional buildings [11]. For a completely passive building that has no need for energy supply, the embodied impacts are, by definition, 100% of the impacts. Low-energy buildings often have lower total lifecycle energy demand, but increased embodied energy [12]. Embodied emissions are, therefore, an important contribution to the environmental impact of new buildings, and the importance is increasing due to the focus on operational energy efficiency. Most of the embodied impacts are occurring during the construction phase of the building, and are therefore possible to influence during building design. Such near-term embodied emissions may also be more damaging than emissions from long-term operational energy use because the decay of carbon in the atmosphere is relatively slow [13]. Shifting emissions from operational to embodied may result in a spike in carbon emissions that could be more damaging, and it is therefore important to avoid such burden shifts. The embodied emissions are, however, difficult to assess properly, since they are highly dependent on system definitions, calculation methodology, and are subject to a lot of uncertainty in the model parameters. In the early phase of building design, limited data availability makes assessments difficult to conduct. On the neighborhood and district level, data availability becomes an even larger issue, and there are little knowledge, methods, and tools available [14]. Life Cycle Assessment (LCA) is the standard approach for assessing the climate change impact of buildings. Many similar, but slightly different approaches to building LCA are practiced today, which can lead to very different results [14; 15]. Therefore, there is a need for improving the consistency and validity of these assessments. Furthermore, there is a need for simplified early-phase assessments, statistical proxy values, and benchmark reference values of embodied emissions.

1.1.2 Material use in the building sector

Material use in the building sector is both a major sector of the economy and a major contributor to climate change. Construction is one of Europe's largest industrial sectors accounting for more than 10% of the EU GDP, with an annual turnover exceeding 1200 billion Euros [9]. Building materials are produced by the manufacturing industry as a result of the demand in the design, construction, and use phases of buildings, as depicted schematically in Figure 1.1. This demand increases supply from the material production industry. In the design phase, the choice of materials and material efficiency strategies determine which materials are produced. In the construction phase, construction waste also increases the demand, and therefore, the production of building materials. During the use phase, the demand for replacement materials leads to increased production, which can be reduced by prolonged use of existing materials. On the contrary, reuse of materials in the end-of-life phase reduces demand for the production of new materials. Consequently, reuse of materials will directly lead to avoided emissions.

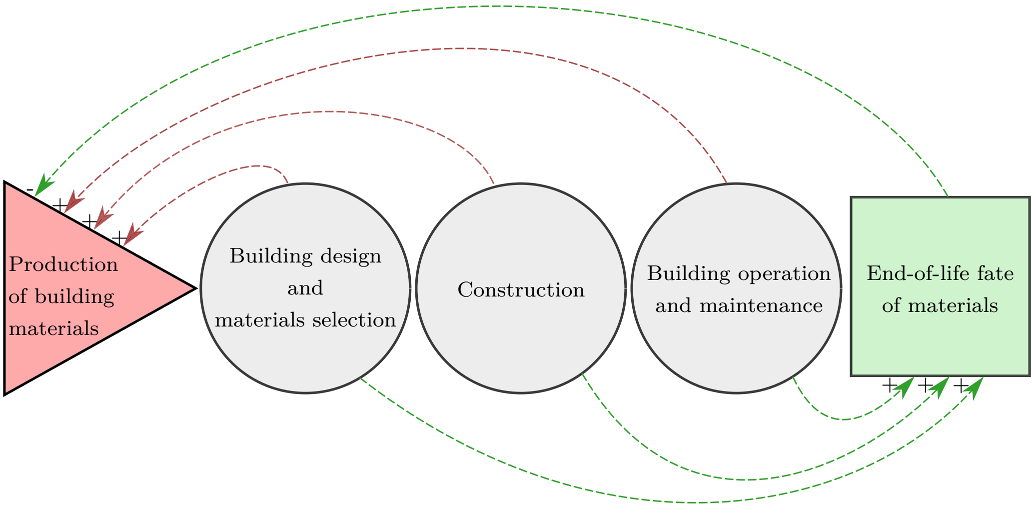

Figure 1.1: Subsectors of a construction industry and connections through price signals. Demand for new materials increase manufacturing while demand for reused and recycled materials stimulates an industry of reuse and recycling which again reduces demand for new materials.

1.1.3 Quantification of climate change impacts of material use by LCA

Life Cycle Assessment (LCA) quantifies environmental impact potentials and resource use of a product or service over its lifecycle, and includes exchanges with the environment from the assessed product as well as the background systems of the product value chain. However, the system boundaries in LCA are dependent on the scope of the study, set by the analyst. All processes are connected to background systems and in the end, the entire global economy is in principle interconnected, but the system boundary must be set somewhere. Any scope will, therefore, leave various processes out and never capture all environmental impacts related to the product. LCA methodology is standardized in ISO 14040 [16] and 14044 [17], although the standards are widely open for interpretation on how to define the product system.

The problem of defining the product system has been approached from a multitude of perspectives, including attributional, consequential, and hybrid LCA [18]. Different LCAs can contradict each other, despite many attempts to harmonize, standardize, and regulate LCA, and it is not realistic to expect LCA to deliver a unique and objective result [18]. Among the family of LCA methods, the most commonly used approach is attributional LCA. However, there are two main problems with the attributional LCA approach: it doesn't take account of the consequences of choosing the product, i.e. how environmentally relevant flows will change in response to possible decisions [19], and it doesn't include all background processes. To address the first of those problems, consequential LCA gives an estimate of how the global environmental burdens *are affected by* the production and use of the product [18]. Attributional and consequential LCA thus respond to different questions, respectively: 'What part of the global environmental impacts is associated with the product investigated?', and 'How does the product affect the global environmental impacts?' [18]. The second problem is addressed by another, complementary approach: Hybrid LCA reveals a more complete impact of the product by capturing more background processes within the system boundary; it does so by alleviating missing data by economic input-output data. Although consequential and hybrid LCA have been argued to, respectively, give a more policy-relevant and complete view of the impacts, attributional LCA is by far the most applied method. This is likely due to, at least to a large degree, tradition and convenience.

LCA can quantify various environmental loads in what is called impact categories. One impact category is climate change, which is concerned with the potential global warming due to emissions of greenhouse gases to the air. This impact category is what is often referred to as the carbon footprint of the product, where emissions of various GHGs are converted to CO_2 equivalents of warming ($kgCO_2e$) over predefined time horizons (THs). This is called the Global Warming Potential (GWP) of the GHG and depends on the decay of the gas in the atmosphere. Carbon dioxide has a GWP of 1, independent of TH, while the GWP of methane varies widely with TH ($9 - 3 \cdot 10^1$ for 20–100 years [20]). Other GHGs are even more sensitive to TH. In practice, a 100-year TH is most commonly used, but this choice of TH is a normative choice based on convention and is not scientifically based [21].

LCA of whole buildings is standardized in EN 15978 [22]. This European standard defines a set of lifecycle phases that are commonly used in research and practice, as shown in Figure 1.2. According to the standard, building LCAs are in principle the combined impact from indirect emissions from material use, often called embodied emissions or embodied carbon (blue), and the direct emissions from energy and water use (orange). Some impacts are considered to be outside of the main system boundary and are reported separately from the main results; these additional benefits and loads are placed in module D (grey). The impact of material use in a building is the sum of the impacts of the individual building materials. The impacts of these

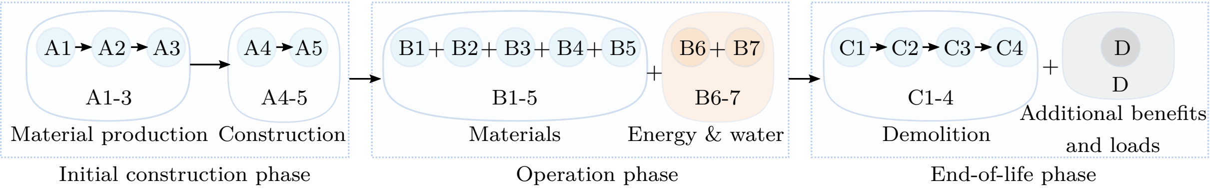

Figure 1.2: Modular approach of lifecycle phases in EN 15978 and ISO 21390. The arrows and plus signs indicate if the processes are happening in succession or parallel.

building materials are usually not calculated from scratch during an assessment of the climate change impact of the building. The impacts are rather gathered from LCA databases, or, as is becoming increasingly common, from Environmental Product Declarations (EPDs) provided by the individual manufacturers or the manufacturing industry. EPDs are third-party verified documents and are standardized by ISO 21390 [23]. This standard uses the same organization of lifecycle phases and processes as for the whole building level, given in Figure 1.2. After gathering such data, the material production impact per functional unit of the material is multiplied by the quantity used in the building to get the impact from use in the building (A1-3). Impacts from the other lifecycle modules are also sometimes provided in EPDs, but even when they are, they will not be specific to the use case of the case building, and can alternatively be estimated based on case-specific data. For estimation of the impacts of transport to the building site (A4), the transport distances and the emission intensity of the transportation modes must be estimated. The remaining construction emissions (A5) are more difficult to assess and requires data on energy use and use of machinery, material waste, etc. at the building site. The impacts due to replacements of materials (B1-5) are usually estimated by assuming standard service lifetimes of the materials, i.e. the time before they are replaced. Similarly, the impacts from the end-of-life phase (C1-4 and D) requires a set of assumptions, and since they occur far into the future they are highly uncertain.

1.1.4 Codes and regulations for GHGs from building materials

Regulations and building codes have long been instrumental for increasing the operational energy efficiency of buildings, while voluntary certification schemes have taken a broader view and included material use [2]. Certification schemes for sustainable buildings such as LEED, BREEAM, and DGNB are partially including LCA in their sustainability assessment [24]. In Norway, the voluntary sustainability initiative *FutureBuilt* has during the previous ten years included a requirement of 50% reduction of GHG emissions relative to a reference building. The program has so far involved more than 50 pilot construction projects. It is largely considered a successful showcase for forerunners in the building sector and a driver for including climate change considerations in the Norwegian industry. The continuation of the program, *FutureBuilt ZERO*, has been launched this year. Instead of reductions compared to reference buildings, the new requirements set absolute limits to the lifecycle impacts on climate change, which gradually becomes stricter with time, following the national climate goals of a 50% reduction of emissions before 2030[1].

As of recently, various national governments have decided to include the carbon footprint of material use in regulations, and are now deciding how this should be implemented. In Europe, some regulatory bodies are now requiring LCA declarations for new buildings. The Netherlands already do so on the country level, while the Norwegian public building administration has requirements in place for reducing the emissions of their building portfolio [2]. In 2018, the Norwegian standardization agency was among the first to release a national standard for

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[1] The author was central in the development of this new methodology which includes many of the novel methodological aspects presented in this thesis work, including the effects of future technological developments, the effect of delaying emissions, biogenic carbon sequestration, and carbonation of cement products. This mentioned work is detailed in section 3.4.3 of this thesis.

LCA calculations of buildings [25], with other countries to follow. Denmark have developed a voluntary building code including an LCA, and several other countries have preliminary work in progress for setting similar requirements, for instance, Sweden, Belgium, and Finland [2]. Sweden will require LCAs to be conducted for most new buildings starting in 2022 and are working to establish limit values that will set absolute requirements for among other emissions related to material use. Similar early work has been initiated by the Norwegian governmental bodies. Reliable benchmark values by which LCA results of new constructions can be compared are therefore becoming increasingly important.

1.2 Limitations and challenges in assessment of embodied emissions

1.2.1 Challenges regarding comparability of results from different studies

There is large variation in reported results of the climate change impact from material use in buildings. Modeling embodied emissions of buildings is prone to large uncertainties, and the actual impacts also vary widely due to the vast amount of combination alternatives of materials and design choices. The ratio of embodied to annual operational energy was in one literature review found to range from 2-72, and the fraction of embodied energy to range from 0.02-0.51 of total lifecycle energy [26]. The study concluded that the majority of journal articles that describe LCA of buildings are not providing sufficient documentation to be useful for comparison. In particular, unit processes and calculation procedures were rarely stated. In a similar study where 206 cases were compared, the ratio of embodied to annual operational energy was found to be quite consistent and reliable, at 7.8 for offices and 7.5 for residential buildings [27]. The authors of this study also emphasize the difficulty of comparing the studies due to the lack of documentation and inconsistency in methodology. The missing information included: which lifecycle stages and sub-stages were included; whether primary or delivered energy was used; building area and area units; description of the building such as location, use, the number of stories, structure type, wall, roof, floor, windows, insulation levels, and type of energy used for heating and cooling [27]. These studies concerned embodied energy, however, the methodology is similar to that of emissions.

There are significant obstacles to comparing results from different studies. Traditional methods of LCA are time-consuming and have to be specifically tailored to individual buildings [28]. They require large amounts of high-quality data for the specific building in question to make an accurate prediction. Even with all the data available, differences in system boundaries from project to project make the assessments almost impossible to compare directly, and little can be stated about the uncertainties of individual analyses without extensive investigations. Furthermore, in LCA methods in general, limitations of data quality and difficulties to assess uncertainty are acknowledged problems [29], and uncertainty analyses are far from being included in most studies [30]. Björklund [30] lists different types of uncertainty appearing in LCA models and ways to improve on this by uncertainty and sensitivity analyses. Khasreen et al. [28] similarly highlight the need for an internationally accepted framework, protocol, and conversion tools to improve comparability of building LCAs, and transparency and higher accuracy of data sets. The paper concludes that, among the LCAs cited in the paper “there are no two studies which could be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used".

The conditions for improving the comparability of LCAs of buildings can be argued to be in an advantageous position. Firstly, there is an increasing amount of such analyses available in the scientific literature. Secondly, many of these analyses have recently been performed in accordance with international and national standards such as, in Norway, NS-EN 15978 [22] and NS 3720 [25] for LCA calculation method and NS 3451 Table of building elements [31] for building parts classification, making them more fit for comparison. Thirdly, although there are important differences, buildings all conform to a similar system boundary; they all require similar materials, building parts, and processes. Therefore, the circumstances for comparing and performing statistical analysis on building LCAs are reasonable.

A comparison can be achieved by a systematic decomposition and classification of the buildings. First, through a decomposition of the buildings' physical parts, with an increasing level of detail; a building has walls, roof, floors, foundation, etc., which again consists of load-bearing and non-load bearing walls, windows and doors, and so on. In turn, each of these building parts is made up of a set of building materials and components that are bought from a manufacturer. Second, each of these materials' and building components' emissions values depends on the system boundaries of emission sources in their lifecycles and the lifecycle of the building.

The challenges involved in predicting embodied emissions of buildings call for new or adapted methods and approaches to be developed and applied. The prediction procedures need to be simplified and further standardized while maintaining the accuracy and applicability of the assessments. The precision of the analyses should be quantified. Particularly, architects, designers, and engineers need reliable prediction tools for early-phase design with rapid feedback loops. In this way, the most influential design choices can be tailored for low emissions in an early design phase when building design choices are not yet locked-in. Although the individual technologies and components to realize a reduction of embodied emissions may currently be available, the lack of infrastructure and tools for data analytics inhibits large-scale implementation. An advancement in this area can lead to better planning decisions being made from an early design phase. Additionally, available data is often insufficiently integrated into decision chains to drive significant changes in planning practice and legal/regulatory environments.

1.2.2 Limitations of existing quantification methods

A very significant variation in the reported climate change impacts of buildings can be attributed to every building's unique location and functional qualities, and it has been argued that LCAs are therefore not comparable [32]. Nevertheless, methodological differences are responsible for extreme differences in results. This has been shown in many comparison meta-studies [26; 27; 33; 3] as well as in methodological sensitivity studies [3; 4]. The following discussion on limitations is organized around the three topics shown in Figure 1.3. Estimation of the climate change impacts from the materials in a building depends on the completeness of the inventory and emission sources, the quality and fitness of the background data, and the calculation methodology and mathematical models.

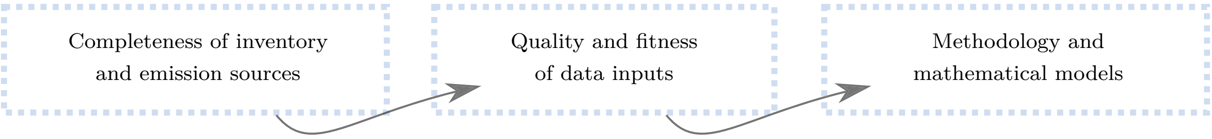


Figure 1.3: Three types of limitations in LCA of building material use.

Completeness of inventory and emission sources. A building is a composition of hundreds of building products, each of which can have equally many connected upstream processes. Furthermore, there are many connected downstream processes during construction, operation, and end-of-life. An LCA study can suffer from limited system boundaries, which will underestimate the associated impacts. Figure 1.4 shows conceptually how any building material LCA study is only a partial footprint of the actual impacts: Not all building materials are included in the assessment, neither are all emission sources related to the use of those materials. This means that some impacts are always left out, irrespective of whether the parameters for each of the included building materials are estimated accurately.

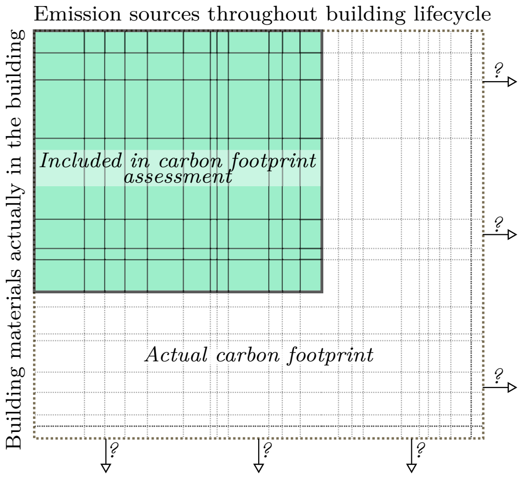
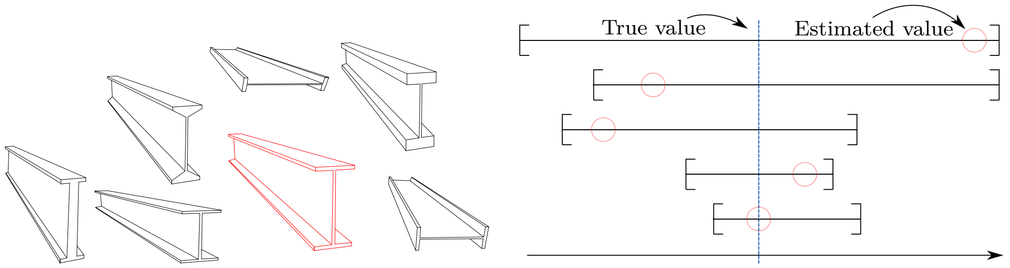


Figure 1.4: Completeness of building LCA studies.

Looking only at the reduction potential of an arbitrary selection of material groups and emission sources will produce a misleading assessment which can lead to misguided design choices. The reduction should rather be evaluated relative to the totality. If a material, a material group, or a building element is excluded from the assessment, then a reference value should be used for the excluded subpart. The emission performance must be seen as a relative reduction for the whole building and not just relative to a selection of building elements, which can encourage deliberate deception if there are economic incentives. Reference values for all building elements can help increase the completeness of assessments.

Quality and fitness of data inputs. Building LCA studies rely on background data from external sources for the climate change impacts of the production of building materials. These data are collected from LCA databases or Environmental Product Declarations (EPDs). Further, the quantities of building materials used in the building must be known, and the transport distances of the building materials to the building site and the service lifetimes of the materials before they are replaced must be estimated. Such data is always approximated and flawed, but the data quality must at the very least be sufficiently accurate for making meaningful estimations of the climate change impact of the actual materials used in the building. The data must match the material, and the estimation must be sufficiently accurate.

The fitness of the data is visualized in Figure 1.5 (a). As an example, imagine that we want to know the climate change impacts of a steel I-beam used in a building. There are many suppliers of steel I-beams from different locations around the world, that use different raw materials, manufacturing processes, energy sources, storage, transport, with different inefficiencies, and so on. The data used must match those conditions. In some cases, the supplier provides an EPD of that specific product, which should take such conditions into account. In other cases, EPDs are not available and generic values of steel I-beams must be used instead. Such average values may be less fit for the specific product. If generic values for I-beams are also not available, an analyst may be forced to use generic values of the metal steel, which further reduces the fitness. Thus, the data must match the actual product used in the building.



(a) Fitness of the data. Does the data match the actual product used in the building?

(b) Quality of the data. How far is the estimated data from the true value? With what certainty?

Figure 1.5: Fitness and quality of data for a steel I-beam used in a building.

Furthermore, the quality of the climate change impact data of the steel I-beam can be close to or far from the true value, and have varying degrees of certainty, as visualized in Figure 1.5 (b). A product-specific EDP is therefore not necessarily better than the generic value of steel, although one can assume that is usually the case. The estimated value of the climate change impacts of the product is not guaranteed to be close to the true value, and in any case, the confidence of an estimated value is never 100%.

Complexity and uncertainty of LCA modeling. First of all, there are different approaches to LCA, and there is a split within the LCA community regarding which modeling framework should be used. Consequential, as well as hybrid LCA, are by many argued to provide more policy-relevant results than attributional LCA. Using a consequential and/or hybrid framework will affect the quality and fitness of data inputs as discussed in the previous section (1.2.2). This thesis solely focuses on attributional LCA because it is currently most applied in building LCA case studies, but the following discussion applies to all variations within the family of LCA methods.

Modeling the environmental impact of buildings is inherently uncertain. Nevertheless, LCAs too often promise uncontested precision [34]. Saltelli et al. (2020) [34] offer five principles that society should demand to ensure quality from modeling: *Mind the assumptions*: global uncertainty and sensitivity should be assessed, i.e. variables, mathematical relationships, and boundary conditions are varied simultaneously as runs of the model produce its range of predictions; *Mind the hubris*: as modelers incorporate more phenomena and complexity increases, predictions typically become less accurate, and thus complexity can be the enemy of relevance; *Mind the framing*: the technique is never neutral, so purpose and context must be matched, and there should be transparency around the normative choices; *Mind the consequences*: unjustified precision cannot be claimed, full explanations are crucial because trust is essential for numbers to be useful; and *Mind the unknowns*: openly acknowledge ignorance. These principles are visualized in Figure 1.6. LCAs of buildings too often ignore all or most of those principles, thereby damaging their trust. In LCA modeling, trust can be gained by adhering to the above principles as follows.

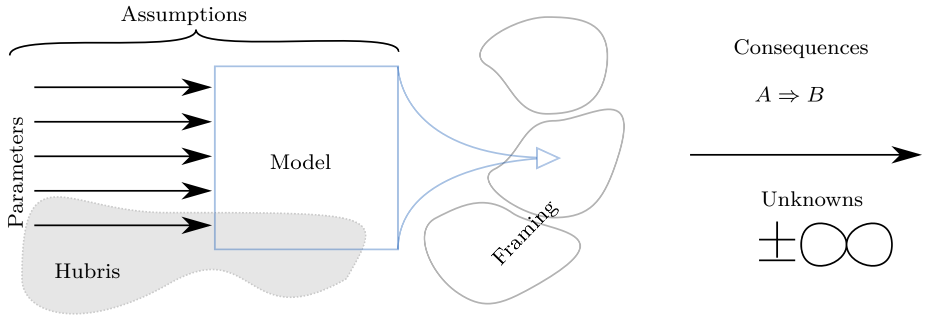


Figure 1.6: Five principles for making models useful to society. Visualization of concepts from Ref. [34].

Assumptions: By exploring the entire parameter space, a global sensitivity analysis (GSA) can determine to which parameters a model is particularly sensitive, and will thereby reveal which parameters that demand high confidence and which do not. GSA stands in contrast to local sensitivity methods, which are limited in their ability to quantify how individual parameters contribute to the overall variability and uncertainty [35]. Sensitivity analysis methods best fit for building LCAs were investigated in [36], who found that the most used methods in building LCA were regression-based or local sensitivity analyses and that the choice of method was rarely justified. The study concluded that the variance-based Sobol analysis was best fit to precisely determine the factors' influence when ignoring its much higher computational cost than other methods. A Sobol analysis is also able to identify interactions and non-linearities. Using this method, the study found the three most influential parameters to be the building lifetime, the time horizon, and the choice of an hourly versus yearly electricity mix [36]. By determining factors responsible for model variance, less influential factors can be assigned default values while priority is given to the most influential, hence simplifying the model description.

Hubris: Complexity should only be added to the model if it reduces the overall uncertainty. Future events are highly uncertain. This should be reflected in the modeling by avoiding superfluous complexity, and the greatest uncertainties should be reduced first.

Framing: The outcome of an LCA highly depends on modeling choices and scenario assumptions

[4]. One normative question that can be asked is how to reduce the building's impact on climate change over a defined time horizon (TH). Within a short TH, future emissions will have less time to warm the atmosphere. LCA studies usually consider the impact over the same TH for emissions happening at whatever point in time (for example, construction and dismantling emissions are both assumed to happen at year 0 and their impact assessed with GWP TH=100 years). According to the IPCC, however, emissions must be cut rapidly if we are to stay within the 1.5°C and 2°C targets, making timing relevant [37].

Consequences: Results of building LCAs are profoundly uncertain, and some parts more than others. The degree of confidence should be conveyed when presenting LCA results, to stimulate effective climate mitigation in the construction industry.

Unknowns: Likewise, unknowns must be clearly communicated. In general, results of unclear LCAs lack significance and inhibit conclusions that could aid in environmental paradigm shifts [4].

1.2.3 Challenges and needs in planning and design

In the following, some important needs for addressing embodied carbon throughout the project phases are identified. These knowledge gaps are addressed by the proposed solutions later in the thesis, where a framework for embodied emission assessment of building materials throughout the planning process of buildings is presented.

Lack of data. The lack of information in early project phases, when little has been decided about the building design and composition, makes it difficult if not impossible to make informed decisions about material use at this stage. However, unknown values is a limitation in all project phases. Collecting data on material quantities, emission intensities, transport distances, the lifetime of building materials, etc. is time-consuming, and the data may not always be available. In the early project phases, unknown values are particularly limiting since little is decided about the building inventory. In later phases, the chosen system boundary restricts the assessment to a selection of building elements and lifecycle phases. To expand the system boundary, there is a need for a method for the estimation of proxy values. The estimated values can then be used in combination with case-specific values to increase the completeness of the assessment in any project phase. A simplified calculation method to calculate the emissions of each lifecycle phase for subparts of the building at various resolutions, would ease the process of mixing case-specific and estimated values and would make early-phase estimation based on statistical data possible. Buildings sharing common characteristics, categorized into building types, are likely to have trends in material use giving each building type a unique emission profile. Statistical results from building types can serve as guidance in early phases when case specific data is unavailable. Statistical insights on the emission profiles and material use of building types can be derived from a sufficient dataset of representative buildings.

Decision-making tool. Most building LCAs take place when all the influential choices have been made, i.e. it is used as a reporting tool, but would be more influential if it was used to inform decisions throughout the process, i.e. used as a decision-making tool. With a tentative building design in place, practitioners need ways to improve the design for further EE reductions.

It is during the planning and design phases that the architects and engineers can influence the EE related to the building design. However, buildings are complex, and the influence of choices on EE is not clear. It is therefore of crucial importance that practitioners are given statistical tools to aid decision making in the planning phases.

Benchmarking. In addition to aiding improved design of the building relative to earlier designs of the building, it would be useful to benchmark environmental performance against other building projects within the same building type. In the design phases, feedback on how the building and its subparts compare to other buildings of the same building type can point the analyst in possible directions for improving the design. In the evaluation phase, benchmarking can serve as documentation for building code requirements and certification schemes.

Verification. Any LCA is subject to the risk of having incomplete system boundaries and inventories. Also, the data used in a study cannot be easily verified but requires extensive investigation. There is therefore a need for a method for verifying both the study design and the data. One way to do so is to control case specific data against statistical data.

Representativeness. Many factors are affecting the EE of buildings, e.g. climate and construction technologies, material production technologies, electricity generation and fuels used, and transport distances. When comparing the EE from one building to those of others, buildings should be categorized by these conditions that have an impact on the EE, such as location, typology (i.e. school, kindergarten, office building, etc.), and construction type (i.e. timber, concrete, steel, etc.). A building type can be general and include many types of buildings, i.e. have few restrictions on the descriptors, or can be specific and include only very similar buildings, i.e. have strict restrictions on the descriptors. By using data from similar building types, the generated statistics and thus the comparison will be more representative of the case. Furthermore, each building consists of an inventory of building materials. Buildings can be broken down into subsets of their inventories, that are here referred to as subparts. This breakdown into subparts of building types makes comparisons more representative, by reducing the variability from both building characteristics and from building inventories.

1.3 Problem statement and research questions

Large variation can be observed in the results from existing carbon footprint studies of buildings. To create an equal basis for comparison and establishing benchmarks, system boundaries and methodologies must be harmonized between studies. Existing building LCA studies contain valuable data that, once the case studies are harmonized, can be used to inform decisions about the choice of materials in the design of buildings. Once harmonized, methodologies can be developed to establish statistical benchmark values for building LCA results. Effective prioritization of climate mitigation efforts requires that impacts are first modeled accurately and with system boundaries that capture all important warming effects. Important contributions to climate change cannot be left out, and it is equally important that the ones that are included are modeled accurately and are matching the goal of the assessment.

This research project set out to harmonize data from existing building LCA case studies and use that data to further develop methods, in a quest for reducing uncertainty and increasing trustworthiness. The developed methods address completeness of system boundaries (both inventory and emission sources); harmonization between case studies; implement dynamic effects such as delayed emissions and technological improvements; and simplify information on material use and related impacts through novel metrics. These objectives led to the following main research question:

Main research question

How can LCA of material use in buildings be improved regarding consistency in inventory modeling, uncertainty and statistical analysis, and accounting of time-dependent effects?

The main research question is answered through a set of specific research sub-questions that separate the conducted research into four research activities.

The first research activity was to develop and compile a database for structuring and storing building LCA case studies. More specifically, creating the basis for an expandable building LCA database that serves future LCAs with baseline comparisons such as reference values for building types and components. As new projects are added to the database, the LCA studies can be documented, verified, replicated, analyzed with different assumptions, calculation methods, and scenarios, and the data from the existing case studies in the database can be used to improve the LCA and benchmark the results. This led to formulation of research question 1:

Research question 1

How can data from previous LCA studies of buildings be structured and used to ensure transparency and consistency in embodied emission sources for building elements and materials, inform decisions in the design phase, and benchmark results?

With a database structure in place, the data can be used to increase the understanding of what determines variations in embodied emissions. Variations arise from design, choices on material use, construction technology, and building morphology, to name some. Results from a statistical analysis can reveal connections between building attributes and emission intensities. Building types and building subparts can be classified systematically by their influence on climate change. Furthermore, the significant uncertainties and sensitivity of parameters involved in building LCAs should be thoroughly investigated. This led to formulation of research question 2:

Research question 2

Which parameters and variables lead to global model uncertainty, and how can statistical analysis generate useful embodied emission information?

Calculation methodologies can be developed further to get more reliable and complete climate change impact results. With systematically structured data in place, the climate change effects based on that data can be recalculated with a variety of methodologies. In a climate change mitigation perspective, it is not greenhouse gas emissions in and of themselves that should be reduced, rather, it is the cumulative warming effect from the radiative forcing of the emissions that is of interest. The cumulative warming effect requires that a time horizon for the warming is defined. Within a defined time horizon, emissions in the near-future are more important than emissions in the far future. Moreover, climate change impacts must be drastically reduced within the next decades and there is thus a time constraint on climate mitigation. Additionally, the building material industry and manufacturing processes are not constant, but are developing with innovation and with electrification of industry processes and transportation. The energy grid is increasingly being based on low-carbon electricity production. These technological improvements gradually reduce the impact from material use in the future. Some emission sources are also highly time-dependent, such as the carbon sequestration and temporary storage in building products. These issues led to formulation of research question 3:

Research question 3

How to better account for technology improvements, carbon capture, and delayed emissions in dynamic LCA, to address climate change impacts over time?

Climate change impacts can be reduced during the planning and design phases, but there is often a lack of data, information, and tools available in these early phases. The database and methodological novelties gained from the research questions above can improve such decision making. This led to formulation of research question 4:

Research question 4

How can such methodological improvements be useful in a planning and design context?

1.4 Structure of the thesis

Figure 1.7 shows the structure of the thesis with the dissertation in part A and the publications in parts B and C. The main contributions of the doctoral work are presented in the highlighted sections, which are placed into context by the preceding chapters, and the proceeding 'Discussion' and 'Conclusions' chapters. The publications are organized by 'Main publications' directly answering the research questions, and 'Supplementary publications' that supplement those. Table 1.1 show which publications answer which research questions. To get an overview of the totality of the work, it is recommended to first read part A, but if specific segments of the work are of special interest, one can refer directly to the publications of interest.

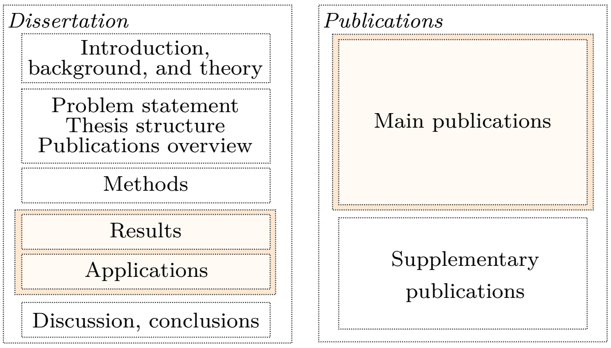


Figure 1.7: Thesis structure with the main scientific contributions in the highlighted chapters.

	Addressed in paper				
Research question addressed	I	II	III	IV	V
RQ 1: Developing and using database.	x	x	x		x
RQ 2: Statistical climate change information and uncertainty.			x		x
RQ 3: Time dependent emissions.		x	x	x	x
RQ 4: Usefulness in a planning and design context.	x	x	x		x

Table 1.1: The research questions addressed by the publications.

1.5 Publications overview

Five scientific papers are included in this doctoral dissertation and are appended in Part B. Four additional papers are related to the research and are appended as supplementary papers in Part C. The papers are numbered in chronological order. Figure 1.8 gives an overview of the papers and how they are related. The main topics and author contributions to each paper are described below.

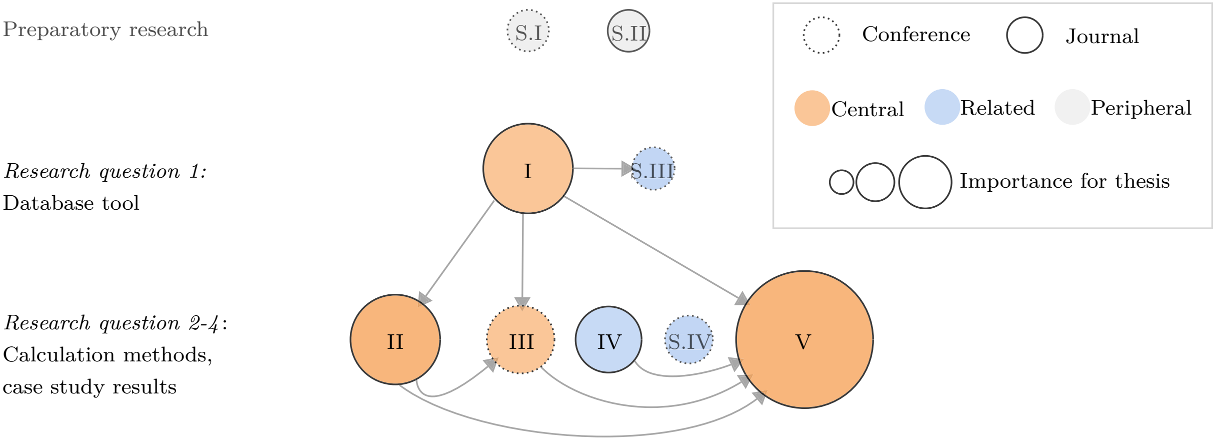


Figure 1.8: Publications in this thesis and how they are related. *S: supplementary paper*

1.5.1 Main topic of papers

I. A database tool for systematic analysis of embodied emissions in buildings.

II. A novel method for evaluation of material-use climate change impacts.

III. Preliminary statistical results based on papers I and II.

IV. Temporal modeling of embodied emissions.

V. Temporal modeling combined with a culmination of methods from papers I, II, and III, in addition to the introduction of novel dynamic methods, statistical results, and uncertainty and sensitivity analyses.

Supplementary papers

S.I Perceived challenges for reaching municipal climate goals, based on semi-structured interviews.

S.II. Municipal energy planning and the role of utility companies, based on the same interviews.

S.III. Applying the database for visualization of embodied emissions in virtual reality.

S.IV Statistical benchmark results from a collection of case-buildings.

1.5.2 List of papers

I. Resch, E., & Andresen, I. (2018). A database tool for systematic analysis of embodied emissions in buildings and neighborhoods. *Buildings, 8* (8), 106.

II. Resch, E., Lausselet, C., Brattebø, H., & Andresen, I. (2020). An analytical method for evaluating and visualizing embodied carbon emissions of buildings. *Building and Environment, 168*, 106476.

III. Resch, E., Brattebø, H., & Andresen, I. (2020). Embodied emission profiles of building types: guidance for emission reduction in the early phases of construction projects. In *IOP Conference Series: Earth and Environmental Science* (Vol. 410, No. 1, p. 012069). IOP Publishing.

IV. Lausselet, C, Urrego, JPF, Resch, E, Brattebø, H. Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. *J Ind Ecol.* (2020); 1– 16. https://doi.org/10.1111/jiec.13049

V. E. Resch, I. Andresen, F. Cherubini, H. Brattebø, Estimating dynamic climate change effects of material use in buildings–Timing, uncertainty, and emission sources, *Building and Environment* (2020) 107399

Supplementary papers

S.I Resch, E., & Andresen, I. (2017). Current challenges of urban energy planning in a Norwegian municipality. In *Proceedings of World Sustainable Built Environment Conference 2017 Hong Kong. Transforming Our Built Environment through Innovation and Integration: Putting Ideas into Action. WSBE17.* Construction Industry Council Hong Kong.

S.II. Nielsen, B. F., Resch, E., & Andresen, I. (2018). The role of utility companies in municipal planning of smart energy communities. *Sustainability and the City*, 213.

S.III. Wiberg, A. H., Løvhaug, S., Mathisen, M., Tschoerner, B., Resch, E., Erdt, M., & Prasolova-Førland, E. (2019, August). Visualization of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality. In *IOP Conference Series: Earth and Environmental Science* (Vol. 323, No. 1, p. 012074). IOP Publishing.

S.IV Wiik, M.K., Selvig, E. Fuglseth, M., Lausselet, C., Resch, E., Andresen, I., Brattebø, H., & Hahn, U. (2021). GHG emission requirements and benchmark values for Norwegian buildings. In *IOP Conference Series: Earth and Environmental Science* (Vol. 000, No. 0, p. 000000). IOP Publishing.

1.5.3 Author contributions

I. The contributions of Eirik Resch were the main elements of research design, gathering of data (together with coauthor), modeling and analysis, evaluation of results and conclusions, and writing of the article with feedback from the coauthors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

II. The contributions of Eirik Resch were the main elements of research design, gathering of data (together with coauthor), modeling and analysis, evaluation of results and conclusions, and writing of the article with feedback from the coauthors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design. Author 2 contributed with text in the introduction part of the paper, and gave general feedback throughout the manuscript.

III. The contributions of Eirik Resch were the main elements of research design, gathering of data (together with coauthor), modeling and analysis, evaluation of results and conclusions, and writing of the article with feedback from the coauthors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

IV. The contributions of Eirik Resch were giving feedback on the method and thus helping shape the results, and the interpretation of the results, the discussion, and conclusions, and giving detailed feedback on the manuscript in multiple iterations.

V. The contributions of Eirik Resch were the main elements of research design, gathering of data (together with coauthor), modeling and analysis, evaluation of results and conclusions, and writing of the article with feedback from the coauthors. Results, discussion, and conclusions were discussed together with supervisors. The supervisors were also central in developing the research questions and research design.

Supplementary papers

S.I The contributions of Eirik Resch were the research design (together with coauthor), gathering of data, analysis of interviews, evaluation of results and conclusions, and writing of the article with feedback from the coauthor. Results, discussion, and conclusions were discussed together with the supervisor.

S.II. The contributions of Eirik Resch were defining the problem definition (together with main author), and providing a portion of the data, findings, analysis, and writing. Results, discussion, and conclusions were discussed together with coauthors.

S.III. Eirik Resch contributed to the ideation and planning of the method from the beginning and throughout the process, he contributed the data used in the paper, and edited and wrote parts of the text. The implementation was conducted by author 2 and 3.

S.IV Eirik Resch performed essential parts of the analysis. More specifically, he performed the statistical tests, calculated some of the statistical benchmark values, contributed to the writing of the manuscript, and the analysis and evaluation of results and conclusions. He also gave statistical methodology advice which helped shape the method. The contribution to the statistical analysis is presented in 3.4.2.

Chapter 2

Research methods and tools

The chapter briefly explains how the research was carried out, which methods and software were used, the data collection, method development, and results. Detailed descriptions of the research methods applied are to be found in the respective papers.

2.1 The research process

The research first set out to map existing challenges and needs for archiving the climate goals of the Norwegian capital municipality through semi-structured interviews, resulting in supplementary papers S.I and S.II. After the preparatory research, the research design shown in Figure 2.1 was established. The research design consisted of collecting existing case studies and structuring the raw data in a database that was developed for the purpose, presented in Paper I. Data collection continued throughout the remainder of the project. This data was used in the development of new methods that produce climate change impact results in various formats, presented in papers II, III, V. During the process, collaboration with other researchers additionally led to the publication of papers IV, S.III, and S.IV. Below, each of the research activities are explained in more detail.

Figure 2.1: Main research design, consisting of the collection of existing unstructured building LCA case studies, structuring them in a purpose-built database, recalculating their climate change impacts with novel developed calcualtion methods that make use of data from all collected case studies, and that ultimately lead to automation of results generation in various formats.

Preparatory research. The research project first set out to map what were perceived needs of municipalities for achieving their ambitious climate goals and for reducing climate change impacts in urban and neighborhood-scale planning. This was done in a series of semi-structured interviews seeking to understand how urban planners and decision-makers work with energy and emission reductions on the neighborhood- and urban scale. The results were presented in two supplementary papers. The findings determined where the needs of the planners are pressing and were used to focus the main research in a useful direction. The following work was addressing the need for a simplified tool to include embodied emissions is a systems-thinking perspective to aid effective climate mitigation.

The focus was placed on developing a framework to automate and simplify the embodied emissions calculations for individual buildings and clusters of buildings in neighborhoods, particularly for early-phase planning. To do so, the average climate change impact of material use in existing buildings can be used to extract guidelines for new buildings in the planning phase. Such average benchmark values needed to be calculated with a harmonized methodology. Early-phase planning can then utilize these statistics to set requirements for embodied emissions of each planned building in the neighborhood or city. Such a framework should provide decision-makers and researchers with guidance on where priorities should be made in the planning process, as well as simplify embodied emission calculations in the early design.

Structuring and developing the database. The goal of the research activity was to create a baseline emissions repository based on existing LCAs of pilot projects, categorized by building attributes, environmental ambition level, and similar categories, with components classified by NS 3451 Table of building elements [31] and the lifecycle modules of NS-EN 15978 [22]. These standards have been frequently used in Norwegian building LCAs. A problem with the collected case studies was varying system boundaries, meaning that case studies also suffered from missing data.

A novel analytical method. The goal of the research activity was to use the established database to get reliable and useful statistical results. To do so, it was necessary to also improve the calculation methodology, which was done by introducing a set of embodied emission subpart metrics. The following research builds upon this method to determine uncertainty and to improve system boundary and inventory completeness (i.e. trustworthiness) of individual LCA studies, which is extremely important, as well as to establish statistical emission profiles of building types, benchmarks, early-phase estimation, and more.

Dynamic aspects. Another important aspect of climate change impact is the temporal dimension. Greenhouse gas emissions are emitted throughout the long operational lifetime of the building, and several dynamic effects will influence the climate change impact. The final part of the research project focused on developing methods for such effects.

Results from case buildings. The collected data from case studies was used to calculate climate change impact results with the developed methodologies. Thus, no full LCA was conducted from scratch, rather, the results rely on primary data from previously conducted LCAs, after study designs were harmonized, missing data was imputed based on data from the remaining case studies, and the LCAs were recalculated in each paper with the respective novel methodological contributions.

2.2 Software, data, and method development

The database tool was programmed in MySQL and provides structured storage of data used in the collected LCAs of buildings. The tool also has the functionality to perform traditional LCA studies based on the data, and store the results from those calculations.

The remaining method development and calculations were coded in the programming language Python. The data stored in the database was queried and used in Python with open-source packages for scientific programming such and NumPy, SciPy, and Pandas. Customization of the Matplotlib package was used to present the results in various plots.

The case studies of LCAs of buildings were gradually collected throughout the research process, both from researchers and from consultancy firms. The case studies all reported data in spreadsheets with no standard format. Thus, restructuring and storing the data in the database allowed for automation of every successive step of the process, such as analyzing data and presenting results in Python. The same calculations could then be applied for all buildings with various calculation methodologies and system definitions. This framework thus provides an environment well suited for continuous method tweaking, exploration, and development.

	Paper				
Aspect	**I**	**II**	**III**	**IV**	**V**
Data (#buildings)	11	1	7	3	20
Novel method	Consistent data	Metrics and technology improvements	Statistical metrics and emissions	Temporal resolution	All the previous in addition to several new
Emission sources	Production	Production, transport	Production, transport	Production	Production, transport, waste incineration, biogenic uptake, carbonation
Lifecycle phases	A1-3, B4	A1-3, B4	A1-3, B4	A1-3, B4	A1-5, B4, C2-3
Software used	MySQL	Python	Python	Python	Python

Table 2.1: Overview of the methods applied in the papers.

Chapter 3

Results

This chapter proposes a framework for the assessment of the climate change impact of material use in buildings throughout all project phases by using a combination of statistical and case-specific data to inform climate mitigation actions. Solutions proposed in the papers is presented as a combined framework in this chapter. The methods are only briefly described, while full descriptions are given in the original research papers.

Section 3.1 provides a summary of all the papers that are part of this thesis.

Section 3.2 proposes solutions to some of the limitations in LCA methodology discussed in 1.2.2. Estimation of the emission sources production, transport, waste incineration, biogenic carbon sequestration, and carbonation of concrete from only limited inventory data and some additional model parameters is outlined. Then, the construction of a dynamic emission inventory and the inclusion of dynamic effects related to technological progress and delayed emissions is explained. The section also introduces a simplified calculation method based on subpart metrics, which can be used for various applications elaborated on in the next section.

Section 3.3 proposes solutions to the limitations and needs for estimation in the planning phase discussed in 1.2.3. Collecting previous LCA studies of buildings and organizing them in a structured database enables the use of that data for the various applications. These use cases lead to several applications throughout the project phases of construction projects. In the early phases, statistical results can inform decisions. Statistics can also replace missing data throughout the project phases, benchmark results, and verify data.

Section 3.4 summarizes the applications of the methods as presented in the main papers, and also presents two additional applications; a separate statistical study, and a climate change benchmarking method meant for application by the Norwegian construction industry, which is based on an adapted version of the methodologies in the papers coupled with results from the statistical study.

3.1 Summary of the papers

Together, the papers form a connected story - a combined thesis. This storyline is given below with a summary of each publication. The papers are organized by *Preparatory research*, *Developing the database*, and *Developing calculation methods and establishing statistical results.*

Preparatory research

Supplementary paper S.I: This analysis uncovered how Oslo municipality's ambitious energy and emission reduction goals were incorporated in the planning practice, through in-depth semi-structured interviews with planners. It was found that there are underlying challenges regarding system definitions, making the right priorities, the transformation of existing urban areas, and that integration between departments to reach common goals has potential for improvement. It was uncovered that stronger implementation of energy and emission assessment in the urban planning practice can be beneficial for achieving reduction goals, but that new assessment methods and tools need to be developed and current tools stronger implemented in decision chains. The study brought some relevant issues into the spotlight: How can quantitative methods be integrated into early-phase planning to aid decisions? There was a lack of knowledge and frameworks for evaluating alternatives, such that planners get an overview of which factors should be considered and prioritized while avoiding problem shifting and including the most important impacts. A selective system definition was forming environmental ambitions and actions in the municipality, which is only considering direct emissions within the municipality borders and excluding all indirect emissions. The reason given for this choice was that the indirect emissions are hard to account for; they lack tools for assessing these emissions. The municipality was therefore focusing on specific actions that they think will reduce emissions, without having a system understanding of how the city contributes to climate change.

Supplementary paper S.II: The focus of the paper is on the role of utility companies in the municipal planning of smart energy communities (SECs). Additional findings from the interviews done in S.I illustrate a clear need for definitions and strategies that can strengthen the role that municipals must take to manage planning towards a zero-emission vision. The paper highlights the need for increased work to create feasible and understandable definitions and strategies for the planning of SECs. There was a confuscation between direct and indirect emissions, and it was not clear what emissions should and should not be attributed to the municipality. The interviewees expressed a need for developing calculation methods and tools for effective accounting of these issues in the planning of smart energy communities. City planners struggle to include energy aspects in the early planning phase, which leads to utility companies taking a leading role. Utility companies respond to the perceived threat of more self-sufficient communities by depicting a role closer to the end-user and by offering a pragmatic cost/benefit view on the planning of energy supply options. Without a clear understanding of energy and emission planning from the municipality's side, utility companies might end up influencing the development of urban areas in a suboptimal way relative to the municipality's energy and emission reduction goals. Clear frameworks and tools that emphasize the system perspective might help municipalities make better choices in this regard.

Developing the database

Paper I: The growing body of building LCA studies from scientific literature and practice is not being utilized, although there is a clear potential. Not only the results, but the complete material inventories and datasets used in calculations can be taken advantage of for various applications. To do so, a database structure was presented in the paper. By systematizing and storing all relevant information for these studies in a compatible format, the data, methods, and results can be transparently reported, verified, and the studies can be replicated. Furthermore, system boundaries and assumptions can be set equal for all case studies, which allows comparison of results regardless of their original system boundaries, data, and methodologies. From these harmonized results, statistical results can be used to set benchmark values for future buildings. Other statistical applications include identifying emission drivers and relationships between variables.

Supplementary paper S.III: This paper presents a prototype where the database was used for visualization of embodied emissions in VR. One direct use case of having structured data in a database is to visualize embodied emissions in 3D models of buildings in a neighborhood. These visualizations can be presented on a screen, but can also be experienced through immersive technologies like Virtual Reality (VR) glasses. Such visualizations of the climate change impacts of building materials can be used in the design phase of the building, as well as to involve a variety of stakeholders.

Developing calculation methods and establishing statistical results

Paper II: This paper describes a method for evaluating and visualizing embodied carbon emissions of buildings. It builds on Paper I, which presented a database tool for storing building LCAs at full resolution for use in statistical applications and further analysis. The lack of a link between the material inventory data and the aggregated results can make it complicated to evaluate building LCA studies. Making use of the structured data in the database, this paper presents an analytical method for evaluating and visualizing embodied carbon emissions of buildings. The system boundary includes the production, transport, and replacement emissions of building materials. Based on the inventory of each building subpart, aggregated and weighted average metrics for the subpart enable detailed interpretation of emissions. The subparts are building elements in a hierarchical organization and material categories. Results are broken down into building subparts and show embodied CO_2e of material production, transport, and replacements, as well as quantity, emission factors, and replacement emission factors of each subpart. Additionally, a method is presented for modeling the effect of technological improvements on future emissions from the replacement of materials. Future embodied emissions from production and transport of replacement materials are adjusted by a technology model that acknowledges that CO_2e from production and transport will improve in the future: Near-future emission reduction should be the main focus. Application on a case study demonstrates that the subpart metrics can be evaluated in relation to the rest of the building to inform design decisions. The method's usefulness in the design process is demonstrated with two proposed visualization methods. For further research, the paper proposes that the metrics can be compared to results from other buildings and that the method enables use of previous LCA studies for establishing statistical reference values (i.e. benchmark values) based on the metrics.

Paper III: Presents preliminary results from the empirical embodied emission profiles and material use profiles of building types. Building types are compared, and each of them is analyzed in more detail. The emissions caused by material production, transport, and replacements are distributed across building elements on different hierarchies as well as across material categories. This is useful for gaining insights into how emissions are distributed, understanding the effect of choices made in the early phases of construction projects, it can be used to establish benchmark values by which the emission performance of buildings can be measured, and to set regulatory limits on the allowed embodied emission levels of building materials analogous to existing regulations on operational energy performance. Results in this publication are based on very limited data and are only initial indications and a demonstration of the method. Paper V presents similar results with an improved methodology applied to a larger dataset.

Paper IV: The paper presents a temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock. Material use and its climate change impacts in the construction and renovation activities of a neighborhood are modeled by combining life-cycle assessment with dynamic material-flow analysis methods. Application on a "zero-emission neighborhood" project under development showed that 52% of the total embodied emissions were caused by material use during initial construction, and that the remaining 48% were due to material replacements in a timeframe of 45 years. It was also argued that emissions occurring far into the future will have a reduced intensity because of technology improvements, which reduced the future emissions by 1/5.

Supplementary paper S.IV: This paper presents statistical results from a collection of LCAs of Norwegian building case studies to help form recommendations for national GHG emission requirements and benchmark values in voluntary pilot programs such as FutureBuilt and in Norwegian building codes (TEK). It can be useful to know the result distributions of previous LCAs, although varying system boundaries and methodological choices highly affects the results. Preliminary emission requirements and benchmark values for Norwegian buildings were established that can be fueled into ongoing work on including embodied emissions in building code regulations. The reference sample of case studies only has aggregated results, and underlying assumptions and system boundaries can therefore not be harmonized. These aggregated results are from 133 assessments in both the 'design' and 'as-built' project phases, as well as from a 'reference' assessment which is supposed to represent the standard practice before mitigation measures are taken. Both the various project phases and various building typologies are analyzed. These results can be used as initial indications for embodied emission requirements and benchmark values in Norway. An extended re-assessment based on the same data, unique to this dissertation, is presented in section 3.4.2.

Paper V: Various concepts, methodologies, and preparatory work in the papers above have led to the unified methodology presented in the final paper. Additional methodological novelties are also presented, and a comprehensive statistical assessment is presented for the climate change impacts of material use. Building LCA results often promise high precision of impacts while ignoring dynamic effects and often using inadequate scope and inventory. A novel solution to account for delayed emissions is presented, along with future technological improvements. Climate change effects of material use in construction, operation, and end-of-life phases are estimated, from production, transport, construction-waste incineration, biogenic carbon-sequestration, and cement carbonation. Missing data in the inventory is imputed, the scope of emission sources and building elements is harmonized together with the calculation method. Building subpart metrics reveal drivers of impacts and are used for generating statistical emission profiles for building types (typology, timber/concrete) and building subparts (building elements, material categories). Thorough sensitivity analyses reveal that using the proposed dynamic method results in lower uncertainty, and that one should pay particular attention to a selection of the most sensitive model parameters. The study concludes that the building industry must focus on interventions with short-term effects, such as low-impact materials in the construction phase and reduced construction waste, to be able to reach the climate goals.

3.2 Methods for estimation of climate change impact of material use

This section aims to give a brief overview of the most significant methodological contributions of the research, while details are left to the papers. First, an overview of how to estimate emission sources is given. Then, methods for including dynamic effects are introduced. Lastly, embodied emission metrics for building subparts are introduced to make use of statistical data in applications.

3.2.1 Modeling emission sources

There are many uncertainties in building LCA studies, but arguably one of the largest is that many emission sources are commonly excluded. Including only a cherry-picked selection of emission sources will be misleading and can lead to misguided mitigation efforts. When planning a building, emission sources throughout the time horizon must be calculated based on the limited information available from case studies in the design phase. The scope of included emission sources are shown in Figure 3.1, and the calculation of each is explained in the following sections. Although the scope is extensive, it is not a complete representation of all climate change impacts of material use. Furthermore, there are large uncertainties in the calculation of each included emission source. The presented framework aims to improve the calculation methodology to reduce uncertainties and to gain more policy-relevant mitigation advice.

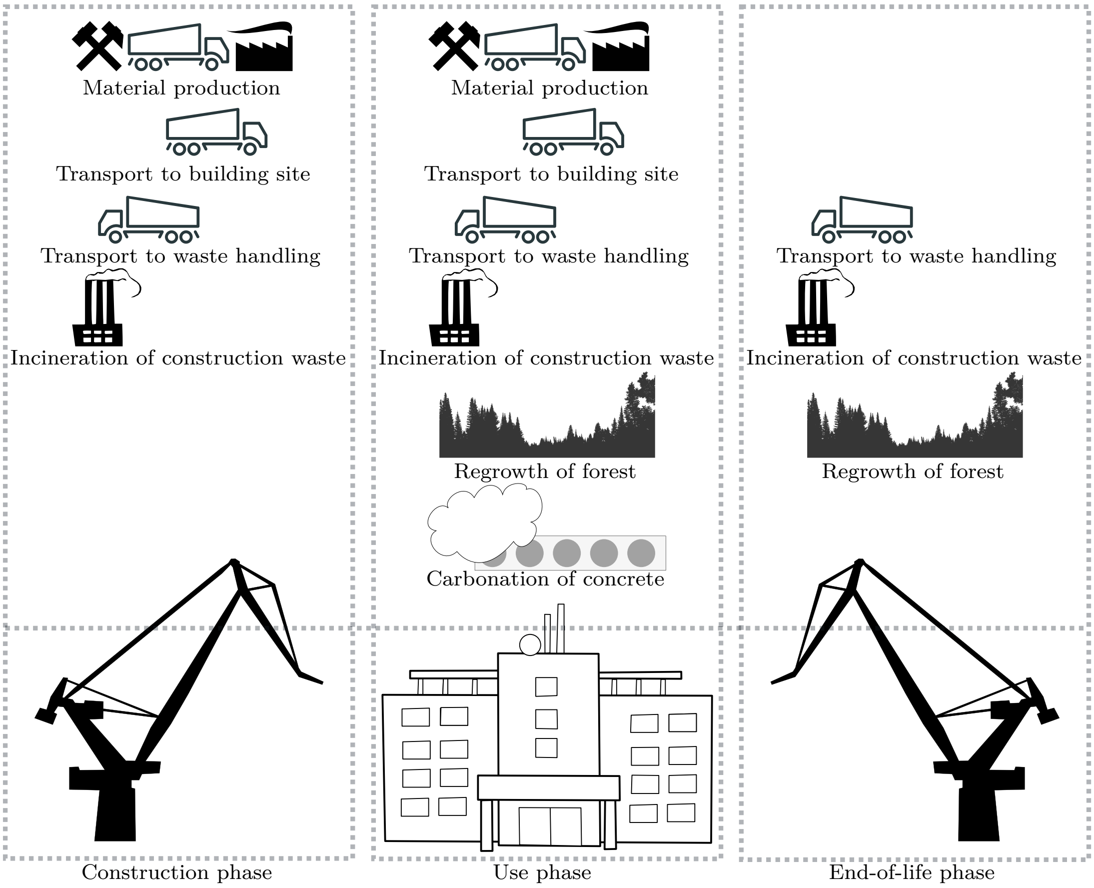


Figure 3.1: Included emission sources in the three lifecycle phases.

Production of building materials. The production of a material includes raw material extraction and processing, transport at various stages, and manufacturing of the final product. The emission intensity of these activities per-unit of building product is here called the emission intensity of production, and in building LCA studies it is collected from external sources. The accuracy of the collected emission intensities of production is beyond the scope of this work. The emission intensity of production is simply multiplied by the material quantity from the building inventory to get the impact of the material. Construction waste must be included in the material quantities so that the production of waste materials is also accounted for. The amount of construction waste can be estimated by adding a fraction to the quantities.

In addition to the production of materials used in the construction phase, some materials will be replaced during the use phase of the building. The quantities of replaced materials and the timing of replacements can be estimated very roughly by the expected service life of each product. The timing of these replacements is uncertain and can be modeled by random variables as explained in 3.2.2. Construction waste must also be included in the quantities of replaced materials.

Transport of building materials to building site and to waste handling. Transporting the building material from the manufacturing factory to the building site is case dependent, as it requires knowledge about the location of the manufacturing plant relative to the building site. The climate change impact of this transport activity is calculated as the product of the quantity (mass of material including construction waste), the distances, and emission factors of the one or more modes of transport used.

The construction waste must be transported to waste handling, which can be approximated by a multiplication of the waste quantities, the distance to waste handling, and the emission intensity of the transport mode.

In the construction phase, the construction waste is the unused remains of the bought materials. In the use phase, the construction waste includes the replaced materials that are removed from the building and construction waste of the new products. At the building's end-of-life, the construction waste is the entirety of materials in the building as the whole building is decommissioned and removed from the building site.

Incineration of construction waste. Construction waste is generated in all three lifecycle phases, and a fraction of the carbon-containing materials will be incinerated. The transformation of biogenic C stored in building products into CO_2 in the atmosphere is dependent first, on the carbon content of products in the building, and second, on the rate of decay (oxidation). At the end-of-life, products are either reused (no oxidation), recycled (zero to partial oxidation), landfilled (gradual oxidation), or incinerated (complete oxidation). Of these, only incineration is considered here.

Incineration of construction waste is a significant source of GHG emissions. For wooden products, the net effect of sequestration of atmospheric carbon dioxide, storage in building products, and future oxidation may lead to climate mitigation. For fossil carbon products, on the other hand, there is a net addition of carbon dioxide to the atmosphere, as the carbon is extracted from long term storage in natural reservoirs. Earles et al. [38] modeled fiberboard, sawnwood (lumber), and plywood products exiting the product pool by a gamma distribution that peaks at 20, 30, and 35 years with 95% removed after 40, 75, and 150 years, respectively, where subsequent landfill decomposition rates are modeled by an exponential decay with country-specific climatic and landfill conditions. Marland et al. [39] also used a gamma distribution to model the product stock, but with a peak of decay in year 150. The net effect of biogenic carbon in buildings over time (both sequestration and oxidation at once) has been modeled directly by the chi-square distribution, for example with 140 years mean half-lives of decomposition [40; 41]. In all these studies large parts of the biogenic carbon remain in building stocks after 100 years, which makes the future fate of construction waste important.

In the method proposed here, it was assumed that 50% of all stored carbon is incinerated. Over the lifetime of the building, this amount is gradually reduced by the future technological improvements explained in section 3.2.2. Because the carbon stored in the building products will attach to two oxygen atoms during oxidation, the weight is increased by 44/12 (the molecular weight of carbon dioxide to carbon) when it reaches the atmosphere as carbon dioxide.

In the construction phase, the construction waste is the unused remains of the bought materials. In the use phase, the construction waste includes the replaced materials that are removed from the building and construction waste of the new products. At the building's end-of-life, the construction waste is the entirety of materials in the building as the whole building is decommissioned and removed from the building site.

Biogenic carbon sequestration. The carbon stored in wood products is in building LCAs most often considered to be oxidized instantaneously at harvest, and the sequestration is modeled as occurring before harvest with no additional sequestration in the regrowing forest attributed to the product. This results in a net-zero carbon flow, which is equivalent to omitting biogenic carbon from the calculations. However, sustainable forest management creates a carbon sink, and it has been argued for a more explicit accounting of the actual emission rates from carbon stored in building products. Assuming instantaneous oxidation of the stored carbon will overestimate emissions drastically [41]. As stated in [41], "Simply assuming that all harvested carbon is instantaneously oxidized can lead to large biases and ultimately overlook the benefits of negative emissions".

Carbon sequestration can be modeled as occurring in the actual trees cut down, which will be before harvest, or it can be modeled as occurring in the new trees growing as a consequence of harvest, which will be after harvest. Both approaches have been used in literature. The choice of harvest or no-harvest will not increase the carbon stored in the harvested trees, however, the choice of harvest will increase the sequestration rate of the remaining forest. Based on this consequential reasoning, the proposed methodology attributes carbon sequestration to the regrowth of new trees after harvest and not to the actual carbon stored in the building materials. The uptake of biogenic carbon during regrowth of the forest is in this methodology modeled mainly by the rotation period of the timber (a rotation period of 100 years is used). The rotation period is the time it takes for a full regrowth of the harvested trees with trees ready for new harvest. Moreover, the regrowth is not uniform throughout this period but changes largely over the years. This dynamic sequestration profile is modeled by the Chapman-Richards growth function. The regrowth rate determined by the parameters of the growth function depends on many conditions and must be estimated. The growth function determines the rate of growth, but the total sequestered amount from the use of wooden building materials is independent of growth rate and is equal to the biogenic carbon dioxide in the products, which is 44/12 of the weight of stored carbon. The sequestration is modeled for all the material categories considered to be based on biogenic materials with an assumption of 50% carbon content.

Carbonation in cement. Over the building lifetime, cement products will bind carbon dioxide from the ambient air in a process called carbonation. Such a carbon sequestration mechanism can give negative emissions that may partly compensate for emissions from the production of the materials. It is uncommon for building LCAs to consider carbonation in cement; however, some such studies were briefly reviewed in [4]. The carbonation rate varies widely between cement-based products and between studies. The sequestration is lower for low-carbon concrete with fly ash or slag. In general, the review found that the carbonation did not deeply affect the net emissions over the product's service life. When crushed and used as recycled aggregate in its next lifecycle, an uptake of ca. 20% of initial emissions can be sequestered, however, that uptake is not considered to be part of the product lifecycle, but rather that of the next use case. Without detailed data on each cement product in the inventory and their exposure to ambient air, it is not possible to accurately assess the carbonation of these products. Nevertheless, a general sequestration model was constructed based on information from [42]. An assumption of 0.1 kgCO_2 uptake per kg cement over 100 years was made. About half of the 100-year uptake happens in the first 25 years, using an exponential decay function $1-e^{-.03y}$ for the sequestration profile in years y in the building lifetime. Carbonation is modeled for products in the material categories 'cement' and 'concrete'.

3.2.2 Dynamic effects

Large parts of a building's emissions occur over long periods, which make LCAs of buildings different from many other products, and this incurs extreme uncertainties for future emissions. This is a crucial point for two reasons; first, technology will improve and future emissions will, therefore, be lower, and second, the timing of emissions is important, and since future emissions are "delayed" they will have less time to cause radiative forcing and global warming within a given time horizon. Both international and national bodies have policies in place for reducing emissions drastically within the coming decades. Today's and near-future emissions are therefore the most important emissions and should be the focus, while future emissions are of lesser importance, and the further into the future the more so. Publications II, III, IV, and V address the likely effect of these mechanisms.

Timing of future emissions. The timing of future production and transport of replacement materials and the timing of waste incineration is unknown and must be estimated. This can be done by distributing future emissions statistically by modeling the timing by random variables. For this, the chi-square distribution is used. This distribution requires only one parameter which is the estimated service life of the material before it is replaced. Statistical distribution of future emissions was used in Paper V.

Technological progress. Technology will gradually improve during the lifetime of the building. Production technologies, material science, and transport technology evolve, and the related processes are gradually electrified by an increasingly low-carbon electricity grid. As climate mitigation initiatives and regulations manifest around the globe, it is reasonable also to expect that reuse and recycling of waste will increase and less will be landfilled and incinerated. In the future, carbon capture and storage (CCS) may be implemented at waste incineration plants, resulting in negative emissions. CCS is a vital part of IPCC 1.5 and 2°C scenarios and is currently being researched, developed, and planned for full-scale projects. In studies that do not account for the societal changes over time due to technology improvements, future embodied emissions are likely to be significantly overestimated. Since the emissions from the initial lifecycle phases take place around the first year of the assessment, no technology improvements apply. In all subsequent years, technology improvements are modeled by adjusting future emissions by the year they occur. Emissions are adjusted by exponentially decaying technology vectors, defined individually for production, transport, and waste incineration. The true improvement rate of these technology improvements is not possible to know with certainty, thus, various scenarios can be defined. Nevertheless, based on historical trends one can with high confidence assume that *some* development will take place, and it is crucial that models estimating future impacts take this into account.

Delayed emissions - climate change impacts over finite time horizons. An LCA of climate change impact always considers the impact over a predefined time horizon (TH), given by the definition of the GWP indicator (usually 100 years). GHGs other than CO_2 are converted to CO_2e using this TH. Building LCA studies usually ignore this TH when accounting for future emissions, which leads to an inconsistency between the TH of the building products and the climate change impact of the building [43; 44]. Furthermore, the climate mitigation goals of governments usually have fixed time spans, i.e. reduce the impacts before 2030, 2050, or 2100. In such (normatively) defined THs, delayed emissions are less problematic than near-future emissions, and this time-dependent effect is important to consider.

Delaying emissions decreases the cumulative heating of the atmosphere over the chosen time horizon, and therefore decreases the temperature rise in the short term. With a long time horizon ($\gg 100$ years), these effects become less significant, and there is no benefit of delayed emissions over an infinite time horizon except for possibly avoiding feedback warming mechanisms. It is therefore important to normatively decide if emissions in the short term are more important than long-term emissions [45]. A dynamic LCA method for including this effect was proposed in [43] and has since been applied in many other studies. In Paper V, a simplified version of this method was developed and applied. The reduced warming effect of delayed emissions is modeled by a novel, simplified methodology, based on weighting future emissions by an exponential decay function, analogous to the exponential decay functions used to model future technology improvements. Future emissions are thus first calculated without considering delay and then adjusted, based on the year they occur, by a delay vector to account for their reduced cumulative warming effect over the chosen time horizon.

3.2.3 Embodied emission metrics for building subparts

Each building can be separated into *subparts*. A subpart is a subset of the material inventory for which emissions are calculated. Average metrics that contain information about the subpart emissions can then be calculated, as was proposed in papers II and V[1]. The metrics are listed below, and are calculated for each subpart:

Quantity and distance
Q: the total quantity of the subpart [kg]
D: the weighted average transport distance of the subpart from the factories to the building site [km]
Emission factors for all emission sources s
α_s: emission factor for phase A; construction [kgCO$_2$e/kg]
β_s: emission factor for phase B; operation [kgCO$_2$e/kg]
γ_s: emission factor for phase C; end-of-life [kgCO$_2$e/kg]
Tech and delay factors for all emission sources s
ω_s: the total reduction effect of the modeled future technology developments
τ_s: the total reduction effect of the delay within the TH

The emission, tech, and delay factors are calculated separately for each emission source s, where $s \in$ [pro, tra, was, bio, cem] are abbreviations for production, transport, waste incineration, biogenic uptake, and cement uptake, respectively.

The metrics can be useful to analyze the material use and emission profile of an individual building, but can also be used for statistical applications. A statistical metric value is for example the average value of all buildings in a building type. These statistical metric values can be used as statistical (1) proxy values in place of missing case-specific data, (2) reference values and ranges by which case buildings can be compared and benchmarked, and (3) emission profiles of building types. Besides, the metrics are related in such a way that they together form a simplified calculation method for the climate change impact of material use; the climate change impact of a subpart can be directly calculated from the metrics. These analytical relationships between the subpart metrics and the climate change impact of the subpart are shown in Table 3.1.

Table 3.1: Calculation of building subpart emissions [kgCO$_2$e/m^2] from aggregation metrics. The emission factors (α, β, γ) are without dynamic effects, which are adjusted for by the tech (ω) and time (τ) factors. Lifecycle phases and emission sources shown in parentheses, e.g A$_{\text{pro}}$. Table is from Paper V.

	Const. (A)	Operation (B)	End-of-life (C)	Adjusted future (B+C)
Production (pro)	$Q\alpha_{\text{pro}}$	$Q\beta_{\text{pro}}$	–	$Q\beta_{\text{pro}}\omega_{\text{pro}}\tau_{\text{pro}}$
Transport (tra)	$Q\alpha_{\text{tra}}$	$Q\beta_{\text{tra}}$	$Q\gamma_{\text{tra}}$	$Q(\beta_{\text{tra}} + \gamma_{\text{tra}})\omega_{\text{tra}}\tau_{\text{tra}}$
Waste (was)	$Q\alpha_{\text{was}}$	$Q\beta_{\text{was}}$	$Q\gamma_{\text{was}}$	$Q(\beta_{\text{was}} + \gamma_{\text{was}})\omega_{\text{was}}\tau_{\text{was}}$
Biogenic uptake (bio)	–	$Q\beta_{\text{bio}}$	$Q\gamma_{\text{bio}}$	$Q(\beta_{\text{bio}} + \gamma_{\text{bio}})\tau_{\text{bio}}$
Cement uptake (cem)	–	$Q\beta_{\text{cem}}$	–	$Q\beta_{\text{cem}}\tau_{\text{cem}}$

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[1] Paper II introduced $Q, F, D, T, L_F, L_{DT}, w_F, w_{DT}$. Paper V used a different notation intended to be more intuitive and consistent: $\alpha_{pro} = F$, $\alpha_{tra} = DT$, $\omega_{pro} = w_F$, $\omega_{tra} = w_{DT}$ and introduced the remaining metrics.

The total climate change impact (CC) from all emission sources s in all lifecycle phases in an arbitrary subpart of a building are

$$\begin{aligned} CC =& CC_{\text{pro}} + CC_{\text{tra}} + CC_{\text{was}} + CC_{\text{bio}} + CC_{\text{cem}} \\ =& Q[(\alpha_{\text{pro}} + \beta_{\text{pro}}\omega_{\text{pro}}\tau_{\text{pro}}) + (\alpha_{\text{tra}} + (\beta_{\text{tra}} + \gamma_{\text{tra}})\omega_{\text{tra}}\tau_{\text{tra}}) \\ &+ (\alpha_{\text{was}} + (\beta_{\text{was}} + \gamma_{\text{was}})\omega_{\text{was}}\tau_{\text{was}}) + (\beta_{\text{bio}} + \gamma_{\text{bio}})\tau_{\text{bio}} + \beta_{\text{cem}}\tau_{\text{cem}}] \\ =& Q\sum_s[\alpha_s + (\beta_s + \gamma_s)\omega_s\tau_s]. \end{aligned} \tag{3.1}$$

Alternatively, the tech and delay factors can be defined individually for each project phase, in which case the equation will be

$$CC = Q\sum_s[\alpha_s + \beta_s\omega_{Bs}\tau_{Bs} + \gamma_s\omega_{Cs}\tau_{Cs}]. \tag{3.2}$$

Each of the above embodied emission metrics is explained in further detail in the following.

Quantity and distance. The total quantity of each subpart is calculated as

$$Q = \sum_{i\in s} q_i\rho_i, \tag{3.3}$$

where q_i is the quantity and ρ_i is the density per kg of material inventory item i.

The weighted total distance of transport of the materials in the subpart is

$$D = \frac{\sum_{i\in s} q_i\rho_i(d_{i,1} + d_{i,2} + d_{i,3} + ...)}{\sum_{i\in s} q_i\rho_i}, \tag{3.4}$$

where $d_{i,1} + d_{i,2} + d_{i,3} + ...$ are the distances of each transportation mode for i.

The emission factors, tech factors, and delay factors of each subpart can now be calculated. The following calculations are performed for each subpart.

Emission factors. The emission factors for a subpart represent the weighted average emission intensity for an emission source [kgCO$_2$e/kg]:

α_{pro}: production emission intensity in construction phase
α_{tra}: transport emission intensity in construction phase
α_{was}: waste incineration emission intensity in construction phase
β_{pro}: production emission intensity in use phase
β_{tra}: transport emission intensity in use phase
β_{was}: waste incineration emission intensity in use phase
β_{bio}: biogenic carbon sequestration intensity in use phase
β_{cem}: cement carbonation intensity in use phase
γ_{tra}: transport emission intensity in end-of-life phase
γ_{was}: waste incineration emission intensity in end-of-life phase
γ_{bio}: biogenic carbon sequestration intensity in end-of-life phase

The emission, tech, and delay factors can be calculated by two different approaches. In the first approach, the inventory data is used directly to calculate weighted averages as was done in Paper II, e.g. α_{pro} of the subpart is calculated as the quantity (q_i) weighted average of the specific emissions f_i of all materials i in the subpart

$$\alpha_{pro} = \frac{\sum_i q_i f_i}{\sum_i q_i}, \tag{3.5}$$

and similarly for all the other factors but with different weights. In the other approach, used in Paper V and the definitions below, emissions of the subparts are first calculated (1) without technology and delay adjustments, (2) with only tech adjustments, and (3) with both tech and delay adjustments, and the factors are then calculated directly from the relationships between these. This second approach is analytically simpler and performed as follows.

The climate change impact of emission source s can be denoted by A_s in the construction phase, B_s in the use phase, and C_s in the end-of-life phase. The emission factors for the construction phase, α_s, are calculated as A_s/Q. It does not matter if the unadjusted A_s or the adjusted $A_{s,\text{adj.}}$ are used since these are equal for the construction phase (no technology improvement or time delay has happened in year zero).

The emission factors for the operation phase, β_s, are calculated as B_s/Q. The unadjusted emissions must be used since the emission factors represent the unadjusted emission intensities.

The emission factors for the end-of-life phase, γ_s, are calculated in the same way, as C_s/Q. The unadjusted emissions must be used since the emission factors represent the unadjusted emission intensities.

The emission factors can be further deconstructed, as was done for material production and transport in paper V[2]. The emission factors for the replacement of materials (use phase) were deconstructed into $\beta_{pro} = \alpha_{pro} \cdot L_F$ and $\beta_{tra} = \alpha_{tra} \cdot L_{DT}$, and the transport emission factor was further deconstructed into $\alpha_{tra} = D \cdot T$, where

L_F: replacement lifetime factor for production of the subpart over the study period [/]
L_{DT}: replacement lifetime factor for transport of the subpart over the study period [/]
T: transport emission factor, per kg and km of the subpart [kgCO2e/kgkm]
L: total replacement factor from both production and transport.

Equivalent deconstructions can be done for the other emission sources.

Tech and delay factors. Future emissions (phase B and C; operation and end-of-life) are adjusted according to an expected future technological development. The tech factors capture the total effect of this adjustment of future emissions into single values. Thus, they quantify the effects of the technological models and will be somewhere between 0 and 1 as long as there is improvement. There are separate tech factors for production, transport, and waste incineration, as well as the total effect for all three

ω_{pro}: reduction effect of future production emissions over the study period
ω_{tra}: reduction effect of future transport emissions over the study period
ω_{was}: reduction effect of future waste incineration emissions over the study period
ω: total technology factor; total reduction in future emissions due to technological improvements

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[2] A different terminology was used for the production emission factor: $\alpha_{pro} = F$

The tech factors ω are all calculated as a fraction of the tech-adjusted emissions to the unadjusted emissions. For example, ω_{tra} is calculated as

$$\omega_{\text{tra}} = (B_{\text{tra, techadj.}} + C_{\text{tra, techadj.}})/(B_{\text{tra, unadj.}} + C_{\text{tra, unadj.}}) \tag{3.6}$$

when the tech factor should represent both future phases, and as

$$\omega_{\text{Btra}} = B_{\text{tra, techadj.}}/B_{\text{tra, unadj.}} \tag{3.7}$$

if the tech factor should only represent the B-phase. More generally, the tech factors are calculated as

$$\omega_s = (B_{s,\text{techadj.}} + C_{s,\text{techadj.}})/(B_{s,\text{unadj.}} + C_{s,\text{unadj.}}). \tag{3.8}$$

Similarly, the delay factors capture the total effect of adjusting emissions according to their timing. Thus, they quantify the effects of the delay model and are always between 0 and 1, where small values would correspond to short time horizons or highly delayed emissions and values close to 1 correspond to long time horizons or emissions occurring in the near future.

τ_{pro}: reduction in future production emissions due to delay
τ_{tra}: reduction in future transport emissions due to delay
τ_{was}: reduction in future waste incineration emissions due to delay
τ_{bio}: reduction in future biogenic carbon sequestration due to delay
τ_{cem}: reduction effect of cement carbonation due to delay
τ: total delay factor; total reduction in future emissions due to delay

The delay factors τ are calculated as a fraction of the tech-and-delay-adjusted emissions to the tech-adjusted emissions. For example, τ_{tra} is calculated as

$$\tau_{\text{tra}} = (B_{\text{tra, adj.}} + C_{\text{tra, adj.}})/(B_{\text{tra, techadj.}} + C_{\text{tra, techadj.}}) \tag{3.9}$$

when the delay factor should represent both future phases, and as

$$\tau_{\text{Btra}} = B_{\text{tra, adj.}}/B_{\text{tra, techadj.}} \tag{3.10}$$

if the delay factor should only represent the B-phase. More generally, the delay factors are calculated as

$$\tau_s = (B_{s,\text{adj.}} + C_{s,\text{adj.}})/(B_{s,\text{techadj.}} + C_{s,\text{techadj.}}). \tag{3.11}$$

3.3 Methods for estimation of impacts in planning and design

The shortcomings and needs regarding building LCA in planning and design, discussed in 1.2.3, are related to the lack of data, tools to process existing data, and comparability between case study results. The construction of a new building goes through several project phases. The information available about the building is scarce in the initial project phase and increases in each successive phase. In the early project phases, a detailed environmental assessment is not possible because of very limited data. This data limitation can be alleviated by using statistical data as a proxy in early-phases which can gradually be replaced by project-specific data as more becomes available. Furthermore, no building LCA, not even in later project phases, has data for the complete building material inventory and all emission sources. Combining case-specific and statistical data will enable increased system boundary completeness throughout all project phases, and therefore form a better basis for decision-making throughout the planning process of buildings. Harmonized system boundaries will also improve comparability between assessments.

3.3.1 Estimation throughout project phases

The methods presented in the papers may be combined into a project-phase framework for assessing climate change impacts of material use. Figure 3.2 shows the project phases and how a combination of statistical and case-specific data can be used for various applications. In the planning and design phases of buildings, statistical emission profiles of building elements and building material categories for various building types can provide insights to inform decisions. Later, when more detailed emission profiles are needed, the unknown subpart data can be approximated by statistical values, and emissions can be calculated with a simplified calculation method based on the approximated subpart metrics. At this point, an initial design exists for which the climate change impact can be reduced by a detailed breakdown and analysis of subparts. Design improvements continue until the construction begins. As more and more case-specific material inventory data becomes available, missing data for the inventory items can be

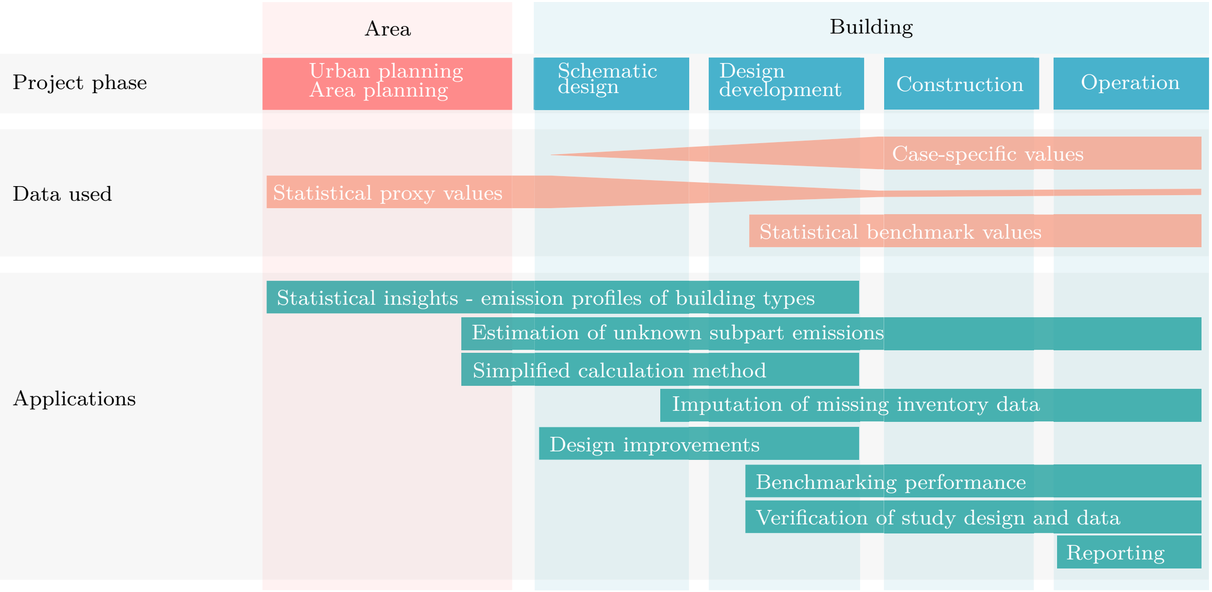


Figure 3.2: Applications and data use throughout the project phases.

approximated by imputation based on data from previous studies. In parallel, the performance of the design can be benchmarked against previous studies, while the same studies may also be used for verification of study design and data. The benchmarking and verification continue in the construction and operation phases. After construction, the structured data allows for transparent reporting of study results and underlying calculations.

3.3.2 Data organization and preparation

Making efficient use of data from previous studies requires that the data is first structured. The database tool provides one way of structuring the data such that the data can later be calculated by any variation of the methods available, and enables several additional use cases. Figure 3.3 shows examples of such use cases: Having data in a coherent format, one has the *flexibility* to recalculate results by different methods, as well as compare an unlimited number of scenarios. Given a representative set of case buildings in the database, *statistics* from those buildings can be used to establish proxy values for material use and related emissions for all the building subparts, emission sources, and lifecycle modules, which can be used for reference in the planning phase or to later substitute missing data. Additionally, statistics for a chosen system boundary and building type can provide the much-requested benchmark values, which can be used to compare new projects in individual studies, certification schemes, and building code regulations. Naturally, *visualizing* the raw data and the results becomes much more convenient, as is demonstrated by the large variety of figures included in the publications as well as by visualization in virtual reality as was demonstrated in paper S.III. Data from previous studies can be used for *imputation* of missing values to be able to use more of the data and to *verify* the existing data as studies are controlled by error checks or checking the feasibility of the values compared to existing data. Study design, system boundaries, and data use are also better *documented*, which means easier reporting and study replication. And because the data is structured, all the use cases exemplified above can be automated by computer programs, thus freeing resources, time, and cost. These use cases enable the applications of Figure 3.2 throughout the project phases. An overview of the database, data preparation, and use is given next.

Database organization. The data is stored in a relational database (implemented in MySQL), consisting of the three main groups of data shown in Figure 3.4: general information about the building and the study, information about the material data collected from external sources, information about each inventory item used in the building, and the climate change impacts of each material item and building element. Further details are given in Paper I.

Missing data and completeness of data. All the collected cases are to various degrees missing data necessary for performing the calculations with an equal system boundary. Missing information can be due to deliberate differences in the study scope (i.e. the system boundary of building elements and lifecycle phases, or only including major product groups), or it can be due to study limitations leading to inaccuracies within the study scope. Missing data thus occurs in *inventory item specification*, in the *completeness of system boundary*, and *completeness of inventory items* within the system boundary. This section describes how such missing data is handled.

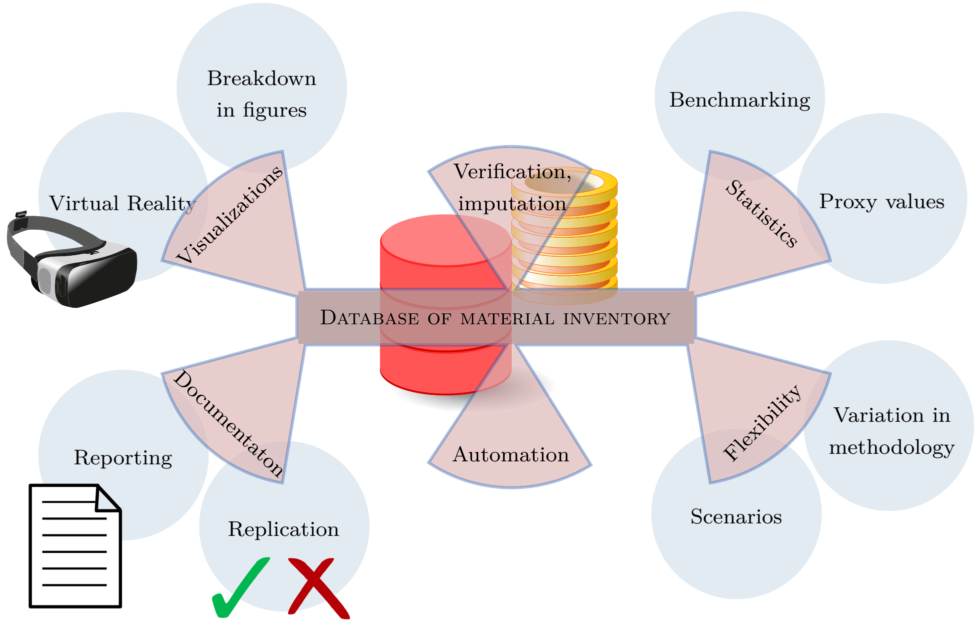


Figure 3.3: Examples of use cases for the database of building LCAs.

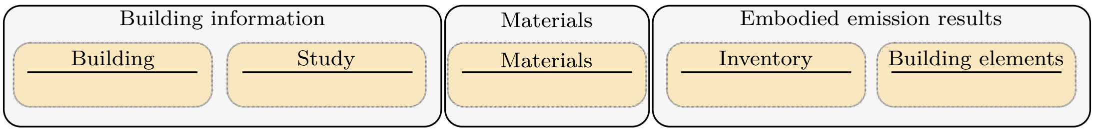


Figure 3.4: Type of data stored in the three components of the database.

If data is missing in the inventory item specification, i.e. the quantity, density, emission intensity, lifetime, transport distance, or transport emission intensity is missing, then that data is imputed by a methodology specifically developed for this purpose where data from the remaining studies is used as a proxy for the missing values. The imputation strategy is explained further down.

Studies with limited system boundaries may be missing entire building elements, emission sources, or lifecycle phases. These missing parts are not a problem in statistical results as long as at least one study has the data, since other case studies that have those parts included will be used for calculation of those building elements or lifecycle phases. For case study results, these same statistical values can be used as approximations.

Missing inventory within the system boundary is more problematic. If studies are missing materials within the inventories of building elements or material categories, it is impossible to detect it directly. Such cases are likely common since all inventories are at the very least missing non-influential details such as screws, and possibly also more influential building materials. Each study is somewhere on the continuum between including only major material groups and including every single material. Missing inventory can therefore be an important source of variation between studies. For this reason, the results from all studies are likely underestimated to some degree, which should be controlled for in future studies.

Imputation of missing data. Among the inventory items of the entire collected dataset, density ρ, material lifetime l, transport distance d, and transport emission intensity t are missing in 52%, 37%, 78%, and 78% of the in total 1860 inventory items in the database, respectively. These are all estimated and imputed based on the remaining inventory in that building and all other buildings. The imputation strategy depends on the feature, and was performed as follows:

The material density, ρ [kg/FU], is imputed based on the mean of all materials with the same functional unit (FU) in the same material category. If that doesn't exist, it is imputed based on the mean of all materials of that functional unit.

The material lifetime, l [years], is imputed based on the mean lifetime of materials of the same material category used within the same building element. If there is no lifetime value for materials from that building element, the building element one step up in the hierarchy of building elements is attempted next, and then another step up after that. If that doesn't exist either, it is imputed based on the mean of all materials within the same material category. If there are no lifetime values for the material category it is imputed based on the mean of all materials in the dataset.

The transport distance from the factory to the building site d [km] is imputed based on the mean of all materials from the same material category. If that doesn't exist, the mean of all materials is used.

The transport emission intensity per weight and distance t is imputed with a fixed value from the Ecoinvent database ('Transport, lorry 16-32t, EURO5'), at .000166 [kgCO_2e/kgkm].

By performing imputation, a fairly complete carbon footprint can be calculated for a case building with only partial information available. Although imputed data is approximated, uncertainty is significantly reduced by a more complete system boundary.

Making use of statistical data. There are two alternatives for the use of numerical values in the calculations, where the use throughout the project phases is shown in Figure 3.2 with the height of the orange bars illustrating the prevalence of the different kinds of data use. One can use data specifically chosen for the case building, or alternatively, statistical data from previous LCA studies that correspond to certain building types, building elements, or material categories.

The case-specific values are used in the design phases of a construction project, to gain insights on how to improve the design in terms of reduced EE. Further, case-specific values are useful in the final evaluation and reporting phases. The case-specific values can also be compared against statistical values for verifying and benchmarking the building LCA.

The statistical values are used as a proxy for estimating unknown values and for creating reference data for certain building types. Statistical values can be used (i) for gaining insights into the statistical emission profiles of different building types, (ii), for estimation when no or little case-specific data is available (of particular interest in the early project phases) (iii) for benchmarking the results of a case study against reference values, and (iv) for verification of study design and data. Along with the statistical values come, whenever there is sufficient data, their corresponding distributions and confidence intervals, thus providing uncertainty for the estimated values. The statistical values will be representative of a case building when sufficient data from similar building types are part of the dataset.

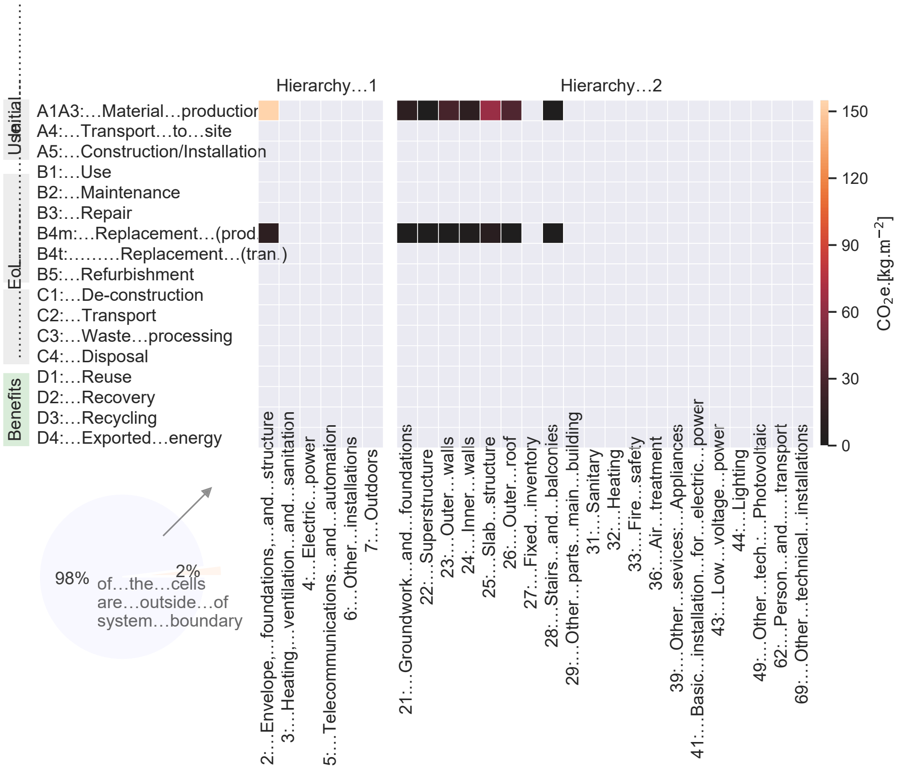
The statistical proxy values are especially useful in the early phases when no or little case-specific data is available. As the project develops, case-specific data will gradually become available and are used in place of the proxy values. The data will at this point consist of a mix of proxy values and case-specific values. However, any project will have time- and economic constraints that limit the assessment's system boundary, and thus limit data collection to a subset of the buildings' complete inventory and their lifecycle phases. Furthermore, emission data for some inventory items will not necessarily be available in the background LCA databases and EPDs where the data is normally collected. Statistical proxy values can in those cases replace the missing data and contribute to the completeness of the assessment, also after the early phases. The completeness varies widely among the case studies that were collected in this dissertation. Some studies had very limited system boundaries, as shown in the example in Figure 3.5 (a). However, combining data from multiple studies increases the completeness of the system boundary, shown in Figure 3.5 (b). The combined system boundary is more complete than that of any individual case building. The figure shows hierarchies 1 and 2 since these are defined in all the collected cases. Many cases also include a third hierarchy that further separates the building elements of hierarchy 2 into subelements. Although a case includes a building element on the second hierarchy, it does not mean that it includes all subelements, and thus the materials of the excluded subelements are not included in the building element on the second hierarchy. Impacts from many such materials are therefore left out of the collected case studies.

Statistical reference values, i.e. benchmark values, on the other hand, do not serve to supplement missing values in an assessment. Instead, they are useful for gaining insights into the emission profiles of building types, and for benchmarking and verifying case-results. The choice of reference values will depend on the use case. The reference values can be specific to the case-building's design and conditions or be based on data for a fairly similar building type, or it can be based on data from, and valid for, all buildings in the dataset.

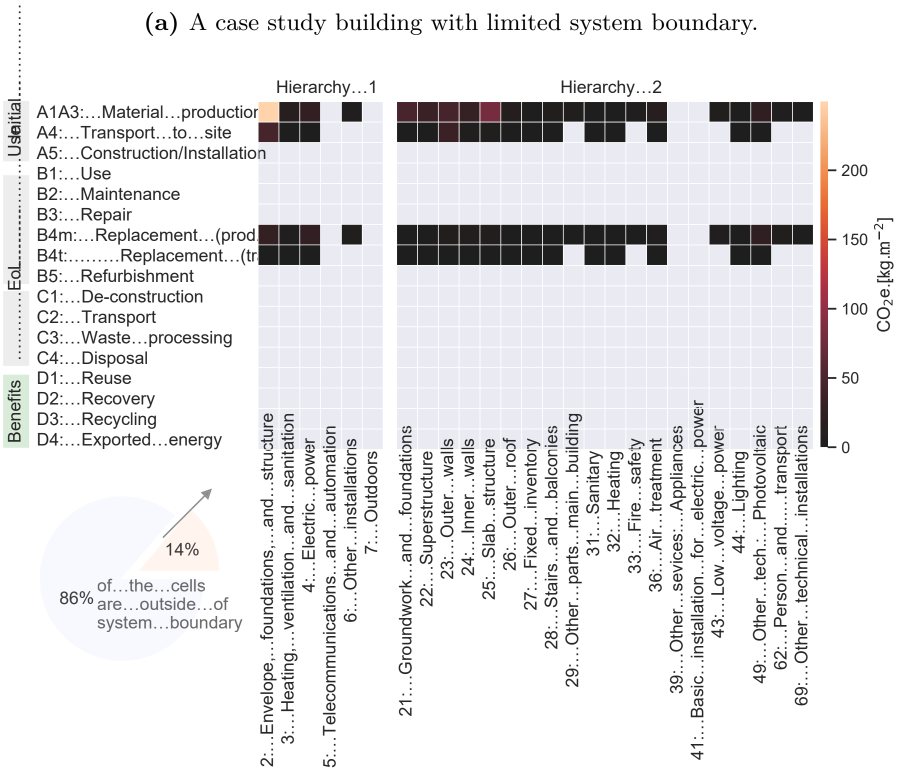
3.3.3 Using statistical subpart metrics

Section 3.2.3 introduced a set of aggregated and average metrics for building subparts. From the inventory data of a building, one can calculate aggregated and average metrics that describe the material use of the whole building or building subparts. A subpart is simply a collection of materials used in the building. The metrics can represent the whole building or individual building elements, and they can represent either all the materials in the building element or be separated into material categories. A selection of material categories in a building element is also a subpart. The buildings' inventory data is linked with the EE results through these metrics that simultaneously serve as a breakdown of the EE results and as an aggregation of the building-specific data.

This section describes how the metrics and equations can be used in different methods of application in a workflow throughout the project phases of a construction project, thus forming a toolbox for working with EE from the early planning to the final evaluation. Statistical subpart



(a) A case study building with limited system boundary.



(b) Combined system boundary of all collected case studies.

Figure 3.5: System boundaries of collected case studies. The combined data from all buildings expand the system boundary and increases completeness.

metrics form the backbone for many possible applications in the planning, design, and evaluation phases of a construction project, shown in Figure 3.2.

In addition to breaking down EE results for a building, the metrics can be used to estimate unknown values. Any subpart of any building type where data is available will have proxy values. Statistical metrics will be representative only of buildings similar to the buildings on which the statistics are based.

Subpart metrics can also be used to calculate emission profiles of building types to gain statistical insights. These emission profiles are obtained by producing statistics for each metric for the building type, broken down by building elements and material categories. From these, the EE of the subparts are calculated. The resulting EE profiles and material use profiles for these building types can be used to inform decisions for reducing EE in the early phases. Such emission profiles can also be used as rough EE estimations in the earliest project phases.

Furthermore, the metrics can together with the equations in Table 3.1 be used as an early-phase calculation method. The case-specific metrics can be used whenever available, while statistical values are used for the metrics where case-specific values are not (yet) available. A building type should first be specified to restrict the statistical dataset to buildings that are representative of the planned building. When no case-specific information is available, such as in the earliest project phases, the subpart can be defined as the entire building, and statistical proxy values may be used for all metrics. As more information becomes available, the building can be separated into subparts and the statistical values gradually substituted by case-specific values.

With a tentative design in place, the metrics can be used to identify design improvements. Breaking down the EE into the metrics allows for analysis of what the driving factors are for the building as a whole and any subpart of the building. Culprits of emission-driving parameters among building elements and material categories can be identified and targeted for reduction.

Besides, statistical metrics can be used for benchmarking the case building metrics and the environmental performance, in the planning and design phases and after construction is complete. Case-specific results are benchmarked against statistics representative of a building type. The performance of each case metric can for example be quantified by its percentile of the statistical distribution of the benchmark metric, and the deviation from the mean or median. This is relevant for assessing the emission performance of buildings, and in policy for integrating emission requirements into building codes.

Parallel to the benchmarking, the metrics can be used to verify study design and data. Case-specific metrics for each subpart can be controlled against statistics of each metric. If a case metric deviates significantly from the corresponding statistical metric, it should be further examined to see if the data used or assumptions are unreasonable.

3.4 Applications

> One must learn by doing the thing; for though you think you know it, you have no certainty until you try.
>
> SOPHOCLES

This section presents a summary of three applications. A proof of concept of the methodologies, as presented in the papers, is summarized in 3.4.1. A separate statistical study is presented in 3.4.2. An adapted version of the methodologies in the papers and results from the statistical study that were combined into a benchmarking method meant for application by the Norwegian construction industry is presented in 3.4.3.

3.4.1 Applications of the proposed methodology in papers

The main methodological contributions are presented in papers I, II, III, and V. Paper V is a culmination of methods from previous papers, where the concepts are combined, tied together, and developed further. One can therefore get a good impression of the applications of the proposed methodological solutions by solely looking at results from that study. Additionally, the dataset of building case studies is larger than in the previous papers which increases the relevance of the results. Before getting to those results, a summary of the applications in the preceding papers is given.

Paper I presented preliminary results mainly to demonstrate some of the database functionality but without the novel methodological contributions to LCA methodology.

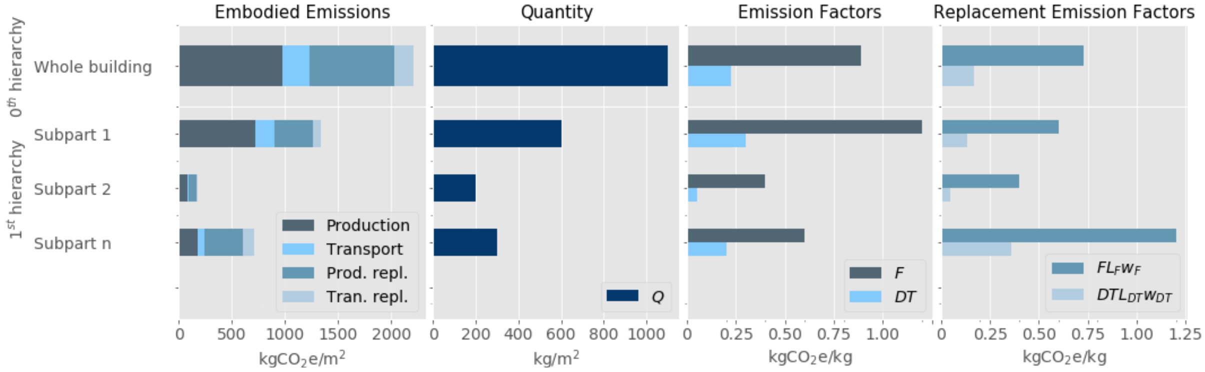
Paper II presented the climate change impact from one case building with the two visualization methods shown in Figure 3.6, this time with a breakdown into metrics and taking account of technological progress.

Paper III presented preliminary statistical results of empirical embodied emission profiles and material use profiles of building types. Building types were compared and each of them analyzed in detail. The results are presented with the same visualization as in Paper II, Figure 3.6 (a) but this time with statistical data based on a collection of buildings.

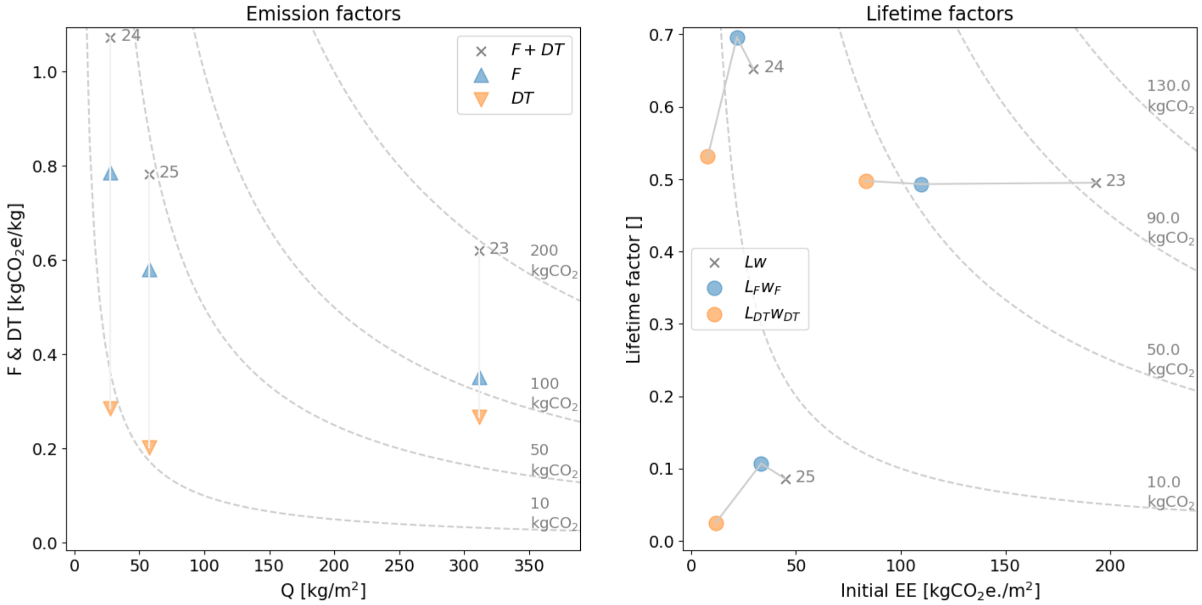
Paper IV presented a temporal breakdown of climate change impacts by year, for a collection of buildings in a neighborhood currently under development.

The final paper, Paper V, ties the applications in the papers above together but also introduces important additional methodological novelties. Figure 3.7 shows the methodological steps. Yearly emissions are first calculated for inventory items and *then* adjusted to the dynamic effects, which are then used to calculate emissions for building subparts, together with aggregated quantities and average emission-, technology-, and delay factors. These metrics are used to calculate statistical emission profiles of building types.

This study includes all the emission sources previously shown in Figure 3.1. Missing data are imputed based on the remaining dataset. Emissions are broken down by their year of occurrence, where future emissions are distributed statistically by random variables. Technological progress is modeled for material production, transport, and waste incineration. The changing global



(a) Climate change, quantities, and emission factor metrics for building subparts.



(b) Two-dimensional breakdown of initial emissions from material production and material transport (left) and the amount that is added throughout the building lifetime for subparts, referenced by numbers (right).

Figure 3.6: Visualization methods used to analyze one case building in Paper II. The figures demonstrate the visualizations; refer to the paper for case study results.

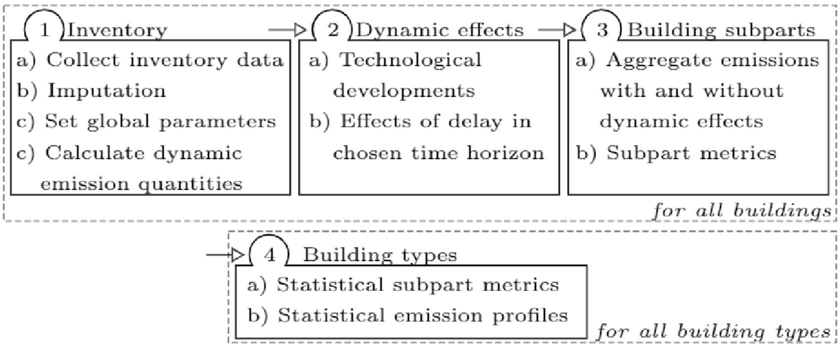


Figure 3.7: Methodological steps.

warming effect due to the timing of emissions within various time horizons (TH) is taken into account. These dynamic emission profiles are presented for one case building in Figure 3.8. The subpart metrics are calculated for all included emission sources. An example of such a presentation of the metrics within a 100-year TH is given in Figure 3.9.

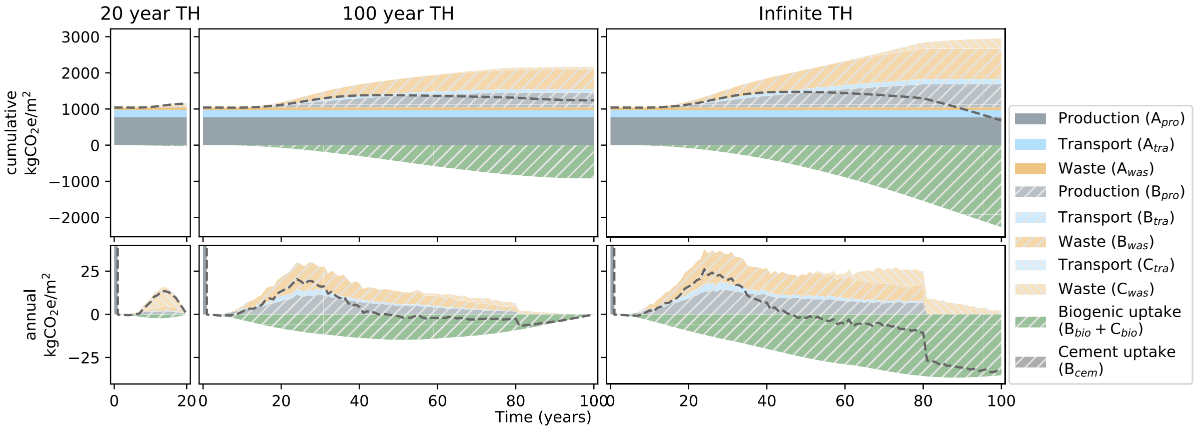
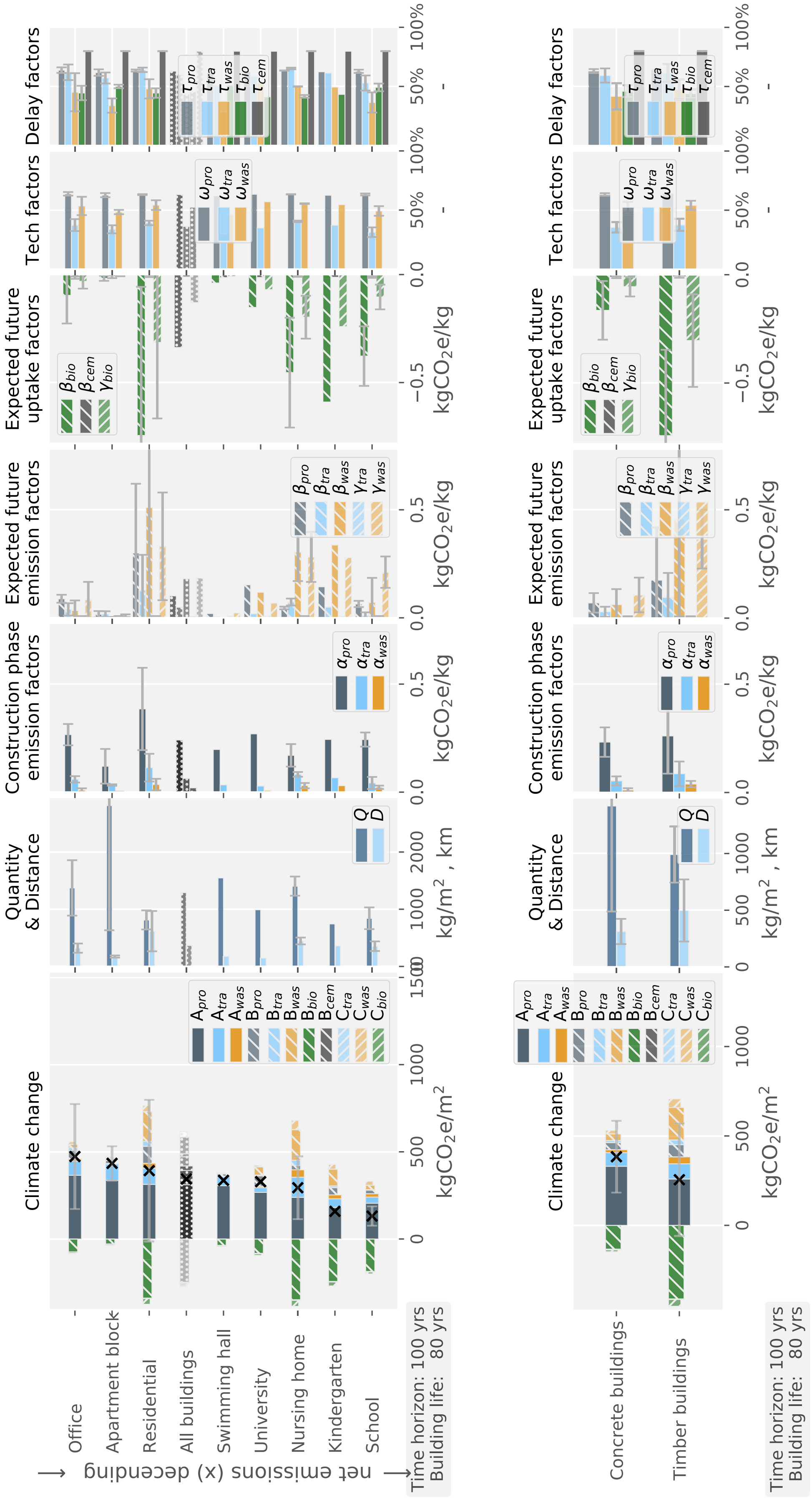


Figure 3.8: Dynamic emission profile of a case building. A 20 year time horizon (TH) is shown on the left, a 100-year TH in the middle, and an infinite TH on the right. Cumulative impacts are shown on the top and annual on the bottom. The case building is 'ZEB Living lab'.

There are many more results in the publication and its accompanying supplementary material. Of particular interest for benchmarking purposes is Figure 3.10, which shows the distributions of results from all case study buildings. Distributions are shown for total emissions, the total of each lifecycle phase, and the total of each emission source, for building element 2: 'Envelope, foundations, and structure'.

Furthermore, variance-based global sensitivity analyses were performed, by sampling thousands of model results while varying model parameters, and then analyzing the contribution of parameters to the variation in the output with the Sobol method. The results are shown in Figure 3.11.



(a) Typologies.

(b) Timber and concrete buildings.

Figure 3.9: Climate change impact of building types, together with aggregated quantities and transport distances, and weighted average emission, tech, and delay factors.

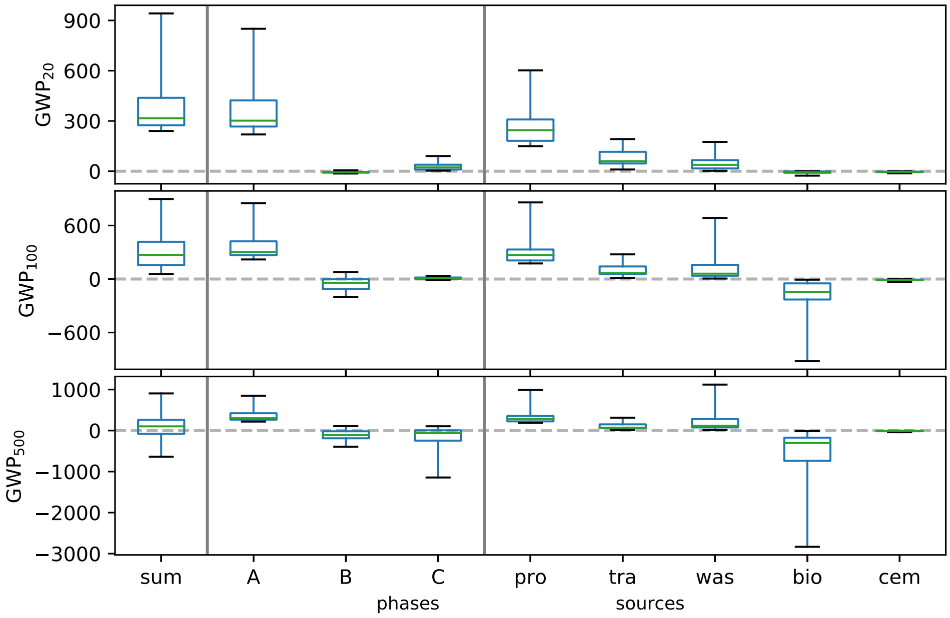


Figure 3.10: Distributions of emissions from building element '2: Envelope, foundations, and structure' for all buildings in three different THs, using 80 year building lifetimes. Showing total sum, sum of each lifecycle phase (construction, operation, end-of-life), and sum of each emission source (production, transport, waste incineration, biogenic uptake, and carbonation). The boxes extend from the lower to the upper quartile with a line marking the median. The whiskers show the range of the results.

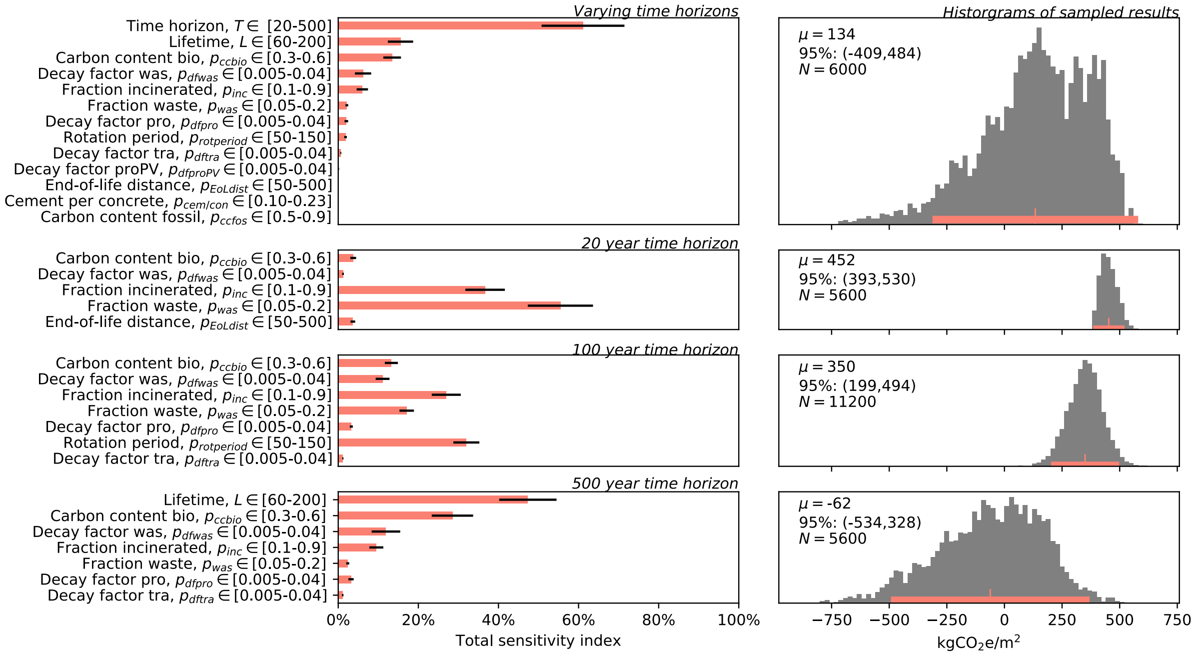


Figure 3.11: The relative contribution of global parameters to total model variance (left) calculated with Sobol analysis based on the Saltelli-sampled model results (right). The results are the total emissions from all sources over all years in the TH for the entire inventory in the dataset (all buildings). The black lines (left) are 95% confidence intervals of the sensitivity indices. The orange bar (right) shows the mean μ and 95% confidence interval of the N sampled results. For the 20, 100, and 500-year THs, parameters that contribute less than 1% are not shown.

3.4.2 Greenhouse gas policies for material use in buildings

The research center for Zero Emission Neighborhoods (FME ZEN) initialized a statistical pilot study for establishing benchmark values of the climate change impacts of material use. The benchmark values are a first step for possible future requirements in the Norwegian building code regulations. A total of 133 building LCA studies were collected by SINTEF for the development of a basis for setting absolute requirements for greenhouse gas emissions from the use of materials in Norwegian buildings. The studies have varying system boundaries, and since only aggregated results were available it was not possible to harmonize the system boundaries and methodology and parameters used. Results are published in paper S.IV and an FME ZEN Report [46], but an updated thorough analysis is presented here. The results on the whole building level are shown in Figure 3.12.

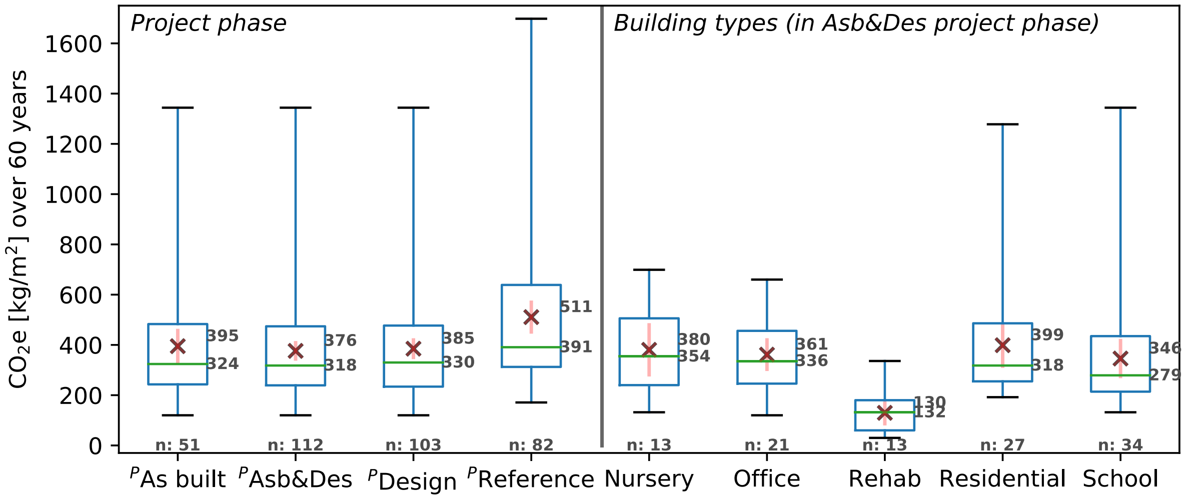


Figure 3.12: Statistical results from 112 case studies; production of building materials for initial construction and replacement throughout a 60 year lifetime. ^{P}= Project phase, ×=mean with 95% c.i., –=median, n=number of observations; numbers show the mean and median. The boxes extend from the lower to the upper quartile with a line marking the median. The whiskers show the range of the results.

Many studies had no results for the ‘As built’ project phase. The ’Asb&Des’ phase, therefore, combines ‘As built’ data with ‘Design’ phase data, which increases the size of the dataset and therefore its usefulness (uses ‘As built’ values if they exist and ‘Design’ values if not). This gives a larger sample and the best estimate of the mean for new constructions. In the right part of Figure 3.12, the building types are therefore calculated with ‘Asb&Des’ values. Data for the refurbishment of existing buildings (‘Rehab’) are not included in the project phase results. The ‘Rehab’ buildings are separated from new constructions and are buildings of all building types, because (1) there is limited data for Rehab, and (2) there is no significant difference between building types based on analysis of statistical significance.

The statistical significance of the variation between averages was tested with paired t-tests for the project phases and Analysis of Variance (ANOVA) for the building types. Based on the available data, the reductions between reference, design, and as-built project phases are highly significant ($p \leq 0.005$, paired t-tests). However, there is no evidence that there is a significant difference between building types (p=0.78, ANOVA, and $p \geq 0.37$, t-tests), except for the 'Rehab' buildings which are significantly lower than all remaining building types ($p \leq 0.0002$, t-tests) since load-bearing materials are reused. Benchmark values should therefore ideally be based on the 'As built' built project phase and be valid for all building types. Only later, when a larger population of cases is available and the differences become statistically significant, one could use benchmark values for different building typologies.

The mean impact in the 'Asb&Des' phase (all building types except 'Rehab') is between 337 and 415 kgCO_2e./m^2 (95% c.i.) or between 5.6 and 6.9 kgCO_2e./m^2/yr (60 year lifetimes), with a median of 318 kgCO_2e./m^2 or 5.3 kgCO_2e./m^2/yr. The refurbishment projects have significantly lower embodied emissions with a mean between 80.0-180kgCO_2e./m^2 (95% c.i.).

3.4.3 FutureBuilt ZERO: An industry certification framework

In the preparatory research, it was uncovered that there is a need for a simplified tool for accounting for indirect emissions such as the embodied emissions of building materials and that there is a need for a clear framework for evaluating alternatives. Together with a panel of industry experts, the methods presented in this thesis were simplified and adopted into a framework meant for application by the Norwegian construction industry.

About FutureBuilt. The FutureBuilt program is the Oslo regions' showcase for the most ambitious players in the construction industry. The vision is to show that it is possible to develop climate-neutral urban areas and high-quality architecture. FutureBuilt's goal is to produce 50 pilot projects - including neighborhoods and individual buildings - that will reduce greenhouse gas emissions by 50 percent in the areas of transport, energy use, and material use. The pilot projects must have a high architectural quality, contribute to a good urban environment, and be close to public transport hubs. FutureBuilt aims to stimulate innovation and changed practices and be a learning arena for developers, architects, consultants, contractors, municipalities, and users. FutureBuilt now consists of 54 completed projects of various typologies. Based on the positive experiences with FutureBuilt 2010 - 2020, FutureBuilt's partners want to continue the program in a new period from 2021 to 2030. The projects that go into FutureBuilt are committed to meeting a set of quality criteria, as well as documenting that these qualities are achieved. In practice, the criteria mean that new buildings must be nearly-zero, zero, or plus-energy levels (the energy requirements for renovation projects are somewhat more flexible). Building materials with low greenhouse gas emissions in production and disposal must be selected, and substances that are hazardous to health and the environment must be avoided. Good location, mobility planning, and environmentally friendly transport measures will reduce emissions from transport in connection with the building. Completely voluntarily, the developers undertake to deliver buildings with higher quality and lower greenhouse gas emissions than required by the building regulations.

About FutureBuilt ZERO. FutureBuilt ZERO introduces criteria for net greenhouse gas emissions over the entire life of the building. The criteria become stricter over time to help Norway achieve its climate goals. FutureBuilt wants to incentivize the choices that will lead to the lowest climate impact from the diverse aspects of buildings. A comprehensive method is therefore introduced that takes into account developments in emissions over time and their contribution to global warming. Both direct and indirect emissions are included, from energy use in operation, from material production and transport of materials to the construction site, both during construction and for later replacements of materials. Included are also emissions from the construction site, and from waste incineration at the end of life of materials. Also, the positive effects of biogenic carbon uptake, from the carbonation of cement, from design for reuse, and exported energy are included. The method and the principles and logic behind it are described in the publicly available criteria document [47].

Overview of the FutureBuilt ZERO methodology. Absolute criteria are introduced for the total climate change impact from all the included emission sources, as well as separate criteria for materials and energy. The criteria are tightened for each successive year to accommodate Norwegian climate goals, as shown in Figure 3.13. The reference value used to set requirements for emissions from material production is based on results from Paper S.IV and the further analysis presented in 3.4.2. As that analysis showed, there was no evidence for separate criteria for building types, thus, there is one common criteria for all buildings. The system boundary for materials is set to the main building, i.e. the envelope, foundations, and structure, and energy production systems (e.g. PV), in NS 3451 [31]. The system boundary restriction is due to the availability of data for creating these benchmark values and will be expanded as more data is collected.

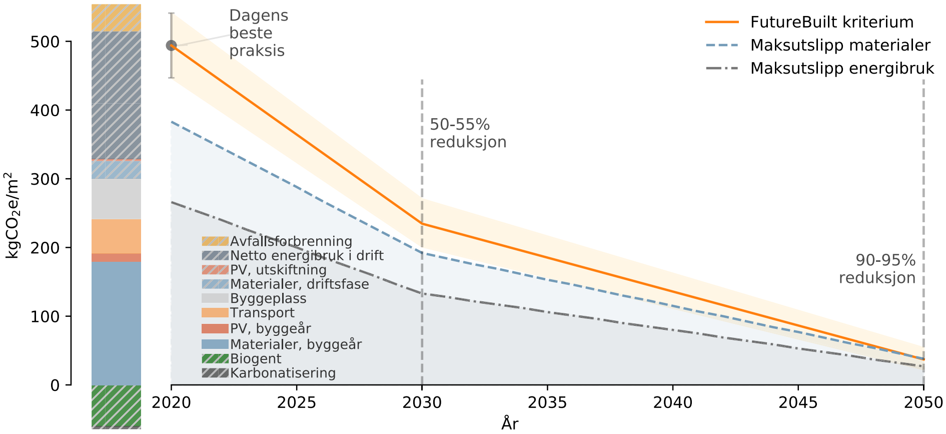


Figure 3.13: Greenhouse gas emissions for 'today's best practice' (orange), and projections based on climate targets. Today's best practice is the starting point for the FutureBuilt ZERO main criterion, which is gradually tightened. For the initial value, a 95% uncertainty interval is also shown, which is similarly projected. Also, separate criteria for material use (blue) and energy use in operation (gray) are shown. Future emissions are shaded in the pillar. From [47].

Technology improvements and time delay are included in the methodology through average tech and delay factors over the period (see 3.2.3). To accommodate practical inclusion of complex climate impacts such as waste incineration, biogenic carbon, and carbonation of concrete, a set of precalculated factors describing these effects are given, that are simply multiplied by either the emissions or the mass of the materials. Emission intensity factors are also calculated and given for energy use in operation. These factors are given in Table 3.2.

Table 3.2: Emission sources and factors. Only the total factor is to be used in calculations. From [47].

	Module	Emission years	Tech factor	Delay factor	Total factor
Construction phase	A_{1-5}	0	1	1	1
Replacement of materials	$B_{2-5,21-29}$	1-60	0.75	0.76	0.57
Replacement of PV	$B_{2-5,49}$	30	0.33	0.77	0.25
Carbon seq. in cement	B_{2-5}	1-60	1	0.83	-0.06
Carbon seq. in forests	B_{2-5}	1-60	1	0.83	-1.27
Waste inc., replacements	B_{2-5}	1-60	0.5	0.76	0.22
Waste inc., end year	C_3	60	0.1	0.48	0.18
Design for reuse	D_{ombruk}	1-60	0.75	0.76	-0.1
Energy in operation	B_6, D_{energi}	1-60	see [47]	0.76	see [47]

Implications and practical importance. The introduction of this set of simplified factors facilitates the uptake of these highly relevant emission sources and temporal effects into mainstream practice in the construction industry and municipalities. The system boundary has been widened substantially compared to existing practice, thus forming a more complete framework which is better suited to inform decisions. This work thus connects the dots of the thesis by addressing the needs found in the initial exploration of limitations in the preparatory research (Paper S.I and S.II), while also addressing those inherent to building LCA with the methodological concepts developed (Paper I, II, III, V), and applying it in a large national ambitious pilot program for the construction industry. The method will be applied to at least 50 construction projects in the coming decade, and will populate the graph in Figure 3.14. This will increase the competence of practitioners and the adoption of the concepts into building LCA practice.

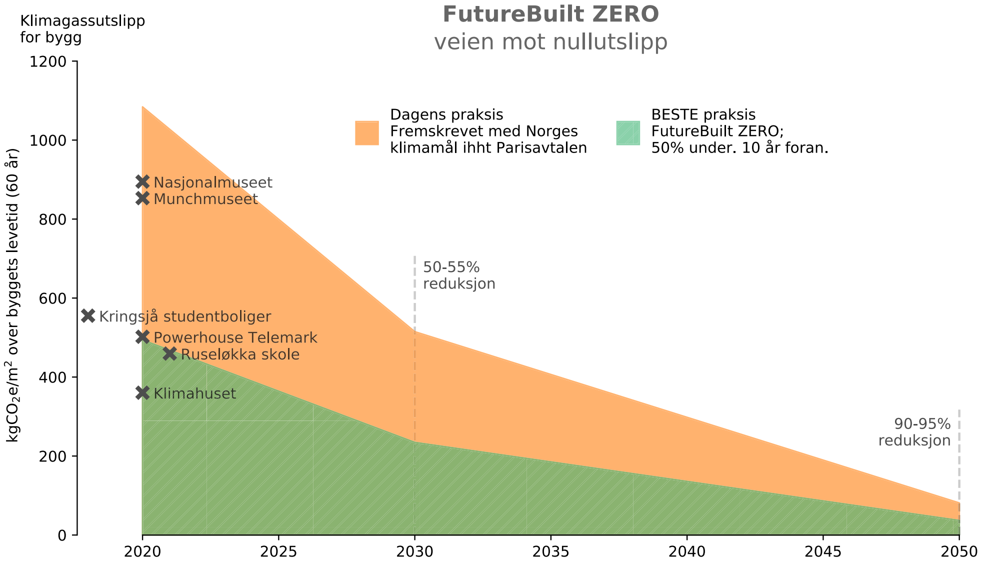


Figure 3.14: The FutureBuilt ZERO criteria and the performance of example buildings compared to the limit values. Orange: Today's normal practice is projected according to national climate goals from the Paris agreement. Green: Today's best practice, also projected according to the same future reductions.

Chapter 4

Discussion

4.1 Main findings

The main research question asked: *How can LCA of material use in buildings be improved regarding consistency in inventory modeling, uncertainty and statistical analysis, and accounting of time-dependent effects?*

The main research question is answered by a combination of the answers to the four research questions below, including a database structure populated with building LCA case study data, sensititivity, uncertainty, and statistical results based on that data, metrics for building subparts, and novel methodological contributions to dynamic climate change impact assessments.

Research question 1 asked: *How can data from previous LCA studies of buildings be structured and used to ensure transparency and consistency in embodied emission sources for building elements and materials, inform decisions in the design phase, and benchmark results?*

A database structure was proposed in Paper I together with results exemplifying its use. The increased transparency and consistency of building LCAs by using this approach were demonstrated by the use of case buildings in Paper I and in successive papers. Looking only at the reduction potential of an arbitrary selection of material groups and emission sources will produce a misleading assessment which can lead to misguided interventions. The reduction should rather be evaluated relative to the a system boundary as complete as possible. Paper II presented a method for aggregating the data into embodied emission metrics for building subparts, and demonstrated how it can be used for improving the design of a building. Paper III and V used the same method to create statistical results for building types, which can inform decisions in even earlier project phases before case specific data becomes available. In the latter cases, the transparency and consistency of this data structuring became apparent as the case studies had to be recalculated with harmonized system boundaries and calculation methods. A consistency of system boundaries across the case studies was achieved by imputing missing data based on data from the remaining studies, by using statistical metric values to estimate emissions of missing emission sources throughout the lifecycle phases, and recalculating the results with primary case study data using the same methodology in a range of scenarios.

Research question 2 asked: *Which parameters and variables lead to global model uncertainty, and how can statistical analysis generate useful embodied emission information?*

In Paper V, a global sensitivity analysis (GSA) quantified the relative sensitivities of individual model parameters and found that climate change results were most sensitive to time horizon, building lifetime (long time horizons only), and waste-related parameters. Paper II proposed a set of embodied emission metrics for building subparts, that were used to generate statistical results for building types in Paper III. The set of metrics was expanded in Paper V, and based on a larger dataset of case buildings, statistical results were calculated from those metrics both for building types (typologies, timber/concrete) and for building subparts (building elements, material categories). The large variation in the statistical results and the results sampling related to the GSA contributes to important knowledge about how to better generate useful statistical EE information. The uncertainty of the results is huge when the values of the global study parameters are not known. To reduce uncertainty, a normative time horizon should be defined, reflecting the goal of the assessment. Technological improvements should be modeled to better reflect reality, but will also significantly reduce the quantified uncertainty. Effort should be made to increase the confidence of the remaining sensitive parameters. The dynamic effects (technological improvements and delayed emissions) significantly reduces the uncertainty of the estimated future emissions. System boundaries were harmonized between studies by imputing missing data and by using statistical proxy values of missing building subparts, which further reduces the uncertainty. Additionally, supplementary paper S.IV and the additional analysis in section 3.4.2 presented statistical results from analyzing a collected set of case study results and concluded that there was a significant difference between the results of different project phases, but no significant difference between building types, except for rehab buildings.

Research question 3 asked: *How to better account for technology improvements, carbon capture, and delayed emissions in dynamic LCA, to address climate change impacts over time?*

Paper II introduced a method for accounting for future technology improvements. The method was developed further in Paper V, which also presented a simplified method for accounting for delayed emissions in dynamic LCA and methods for estimating the carbon capture related to forest regrowth and carbonation. The presented solutions for including the time-dependent effects of technology improvements and delayed emissions are simple to implement, understand, define, and makes it convenient to apply these effects to any climate change results as long as the emissions have a time-resolution, and further, to calculate results for a range of future scenarios. A simplified climate change benchmarking method, based on these methods, and meant for application by the Norwegian construction industry, was presented in Section 3.4.3. Additionally, a dynamic LCA was performed for a neighborhood in IV.

Research question 4 asked: *How can such methodological improvements be useful in a planning and design context?*

This thesis provided an overview of shortcomings and needs related to LCA in planning and design in 1.2.3. Section 3.3 proposed methods for handling those, and thus elaborated on suggestions proposed in papers I, II, III, and V. Those papers additionally presented various ways of visualizing results to guide emission reduction in planning and design, which was also done in supplementary paper S.III.

4.2 Agreement of findings with literature

When comparing benchmark results from different studies, one must be aware of differences in methodology and scope. In many cases it does not make sense to directly compare the findings of this thesis with findings from literature, but the findings can still be placed into perspective. First, the agreement of the results from the different studies included in this Ph.D. work will be compared to each other, then, the results will be placed into the context of existing scientific literature.

The FME ZEN benchmarking pilot study described in Section 3.4.2 resulted in an average impact between 337 and 415 $kgCO_2e./m^2$ (95% c.i.) for production of building materials, mostly from building element '2: Envelope, foundations, and structure' for initial construction and replacement throughout a 60 year lifetime. These results are likely underestimated since the system boundaries and level of detail in the studies are not complete and the studies are not harmonized. On the other hand, technological developments and the delay of emissions are not considered in those case studies, which would have reduced the impacts from the future replacements.

Comparing those results to the average impact between 249 and 434 $kgCO_2e./m^2$ (95% c.i.) from Paper V, shown in Figure 3.10, it falls within this range. The production emissions used in this comparison are using a 500 year TH (will not significantly reduce delayed emissions) and an 80 year building lifetime, and are not far from the system boundary of the FME ZEN study, although waste materials and technological improvements are included.

Paper II analyzed only one case study, which was also included in the benchmark values above (where it was an extreme outlier) and thus the $\sim$ 750 $kgCO_2e/m^2$ for the production of initial material use and technology adjusted production of replacements is not fit for a direct comparison. The 7 buildings used to establish benchmark values in Paper III are also included in Paper V, and are therefore also not of interest to compare directly.

In the uncertainty and sensitivity analysis of Paper V, it was found that results are highly sensitive to changes in model parameters, which confirms the findings of [3; 4]. Building lifetime and time horizon were found to be the two of the most influential parameters, which agrees with the findings of [36], using the same sensitivity analysis method. In literature, meta-studies have reported statistical embodied emission results. In one study [33], the first and third quartiles of embodied emissions ranged between 0.1 and 0.5 tons CO_2e/m^2 for residential buildings and between 0.3 and 0.5 tons CO_2e/m^2 for office buildings[1]. Although the range is larger, results are on par with the findings of this thesis work, but in the study from literature there is no distinction between methodological choices and no separation between emission sources, building elements, and lifecycle phases, making direct comparison challenging. Another study [3] reported

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[1] Converted to a functional unit of heated floor area over a 50 year lifetime, which was the lifetime used in most studies.

construction phase emissions varying between 0.03 and 2.00 tons CO_2e per m^2 gross floor area, but with significant methodological differences between the included studies.

In general, no conclusion can be drawn from comparing these results from literature with the ones from this dissertation due to significant methodological differences, but it can be observed that the results very roughly agree. The benefit of the results presented in the dissertation is that all case studies are calculated with equal methods and largely harmonized system boundaries, thus it is of more interest to compare the buildings *within* these benchmark values to each other, than to those of other studies. Interestingly, there is a large variation in the results between the case studies, even after harmonization. These differences can be ascribed to variation in building desing and material use, in addition to the remaining unharmonized methodological aspects.

4.3 Strengths and weaknesses of the work

With structured data in place, the building LCA studies can be filtered by any building type descriptors, system boundaries can be harmonized, and results can be recalculated with any choice of calculation method. With building LCA data available in this format and at this resolution, any arbitrary subpart of the building can be analyzed with the subpart metrics methodology. Statistics of those subpart metrics can be used to calculate statistical climate change impacts. The representativeness of the produced statistics and thus the comparison between buildings is therefore increased by the division of buildings into subparts. Similarly, dividing a building into subparts can reveal detailed information about how emissions are distributed between building subparts on average.

The applications dependent on statistical metric values are only valid if the dataset on which they are based is of sufficient quality and quantity. Statistical values will only be representative of the buildings contained in the dataset. Consequently, the validity will increase as the dataset expands, as will the utility of the method. Nevertheless, the results are based on case studies and may vary significantly for other buildings. A large and varied dataset of buildings is needed for making general conclusions. Considering the high uncertainty surrounding the replacement emissions, and their lesser magnitude, replacement emissions should not be given as high priority as initial emissions, but we strongly recommend that they are included in building LCAs, as a high completeness of the system boundaries is important.

In Paper V, model assumptions and data is harmonized by setting some parameters equal for all case studies in the dataset. These global study parameters, shown in Figure 3.11, ensure that the calculations of each study is compatible with every other. Further research is needed to precisely determine these parameters. One way to avoid large parts of the uncertainty is to use project specific values for waste fractions, incineration fractions, carbon contents, and rotation periods of each material inventory item. This would yield much more precise results than assuming average values for all materials.

4.4 Implications for policy and research

This thesis proposed methods that better aid the reduction of building materials' contribution to climate change. First, each emission source needs to be quantified correctly and must correspond to the goal of the assessment. To do that, the research questions must be clearly defined, and a TH should always be actively chosen. Planned actions in response to LCA results should further correspond to the degrees of certainty of the estimated impacts.

Many of the methods presented in the thesis are disseminated through the new criteria of FutureBuilt ZERO, thus addressing the challenges and needs found during the preparatory research. There are also plans underway to incorporate FutureBuilt ZERO in BREEAM Norway, and discussions are ongoing with Oslo Municipality and the climate department on how FutureBuilt ZERO can become part of the municipal climate strategy and policy formulation when it comes to addressing indirect emissions from urban development and construction activities. FutureBuilt ZERO is a highly practical, simplified version of many of the concepts presented in this thesis, which facilitates adoption.

In research, and in construction projects with enough resources, the complete methodology presented in the thesis should rather be used. It allows for high flexibility, scenario analysis, and further methodological development.

Importance of delayed emissions and technological improvement. In paper V, the tech factors cause roughly a halving of future emissions (B- and C-phases), and the delay factors roughly another halving on top of that.

A major advantage of the method offered in the study is that the temporal assessment of dynamic effects reduces model uncertainty. Future technological progress is uncertain, indeed, but the assumption of *some* development is better than *none*; including the phenomena of technological progress improves on previous methods. The inconsistency of products with different THs is resolved by accounting for delayed emissions. An additional benefit of factoring in the timing of emissions is that the discounting is inversely proportional to the uncertainty due to time. The further into the future, the larger are the uncertainties, however, these increasing uncertainties will be offset by weighting emissions by their distance into the future. Technological development has the same uncertainty-reducing property. Results are also less sensitive to uncertain parameters such as building lifetime. By significantly reducing the uncertainty of postulated future impacts, this is an important step in the direction of more policy-relevant modeling. The shorter the TH, the more the results can be trusted.

Importance of carbon capture in concrete and wood materials. In Paper V, buildings with larger quantities of wood tend to have lower emissions, both due to biogenic carbon sequestration and lower emissions from material production, where wood products substitute the use of higher emission intensity products. The high waste emission factors (α_{was}, β_{was}, γ_{was}) for buildings and subparts with large quantities of wood products is compensated by high uptake factors (β_{bio}, γ_{bio}), especially in long THs. The carbonation factor (β_{cem}) is low compared to other emission factors; its mean value for all buildings lies within -13 and -8.5 gCO$_2$ per kg of all building materials in the buildings (95% confidence). Carbonation accounts for an average of $4 \pm 1\%$ (95% confidence) of total construction phase emissions for all buildings, given a 100-year lifetime and an infinite TH. Shorter lifetimes and finite THs reduce the importance.

Critical variables and global model uncertainty. The principal sensitivity analysis can be found in Paper V, where model parameters are analyzed in a variance-based global sensitivity analysis. All parameters are varied simultaneously across their entire parameter spaces and ranked according to their relative contribution to model variance. Parameter sensitivities highly depend on the TH, which is a normative choice. GSAs are therefore performed for varying (20-500 years) as well as fixed (20, 100, 500 years) THs. When TH is allowed to vary together with the parameters, it is by far the most sensitive model parameter and is responsible for $61 \pm 10\%$ (95% confidence) of the model variance, followed by building lifetime at $16 \pm 3\%$ (95% confidence). The remaining sensitivities relate mainly to the end-of-life incineration of construction waste and biogenic carbon sequestration. The sampled results vary widely, between -0.3 and $+0.5$ tons CO_2e/m^2 (95% confidence). Thus, climate change impact cannot be determined with any meaningful accuracy without specifying TH; results are not very useful for policy if the sensitive parameters are not precisely known.

For shorter THs, however, results become much more precise. With the assumption of an accurate material inventory, 95% of results are between 0.39 and 0.53 tons CO_2e/m^2 in a 20-year TH, and between 0.20 and 0.50 tons CO_2e/m^2 in a 100-year TH. In the 500-year TH, the variation is on scale with the GSA where TH varies. Thus, shorter THs yield more precise results, while long THs (i.e. predicting impacts far into the future) are highly uncertain. Parameter sensitivities change in short THs: building lifetime is not relevant for THs around 100 years or shorter. The rotation period is highly sensitive for the 100-year, but not for other THs.

Independent of TH, carbon content of bioproducts, fraction incinerated, and waste fraction are always highly sensitive. This calls for refining both the modeling of these effects and the data inputs used, to reduce these uncertainties. These parameters should be determined specifically for each inventory item in each case study, which would reduce uncertainty significantly. For policy, it suggests that limiting construction waste and increasing reuse, recycling, and CCS should be high priorities.

Values of sensitive parameters should be chosen with care. Uncertainties of insensitive parameters do not affect the model output much, hence, it is less important that these are precise. The TH should be a deliberate normative model choice defining the temporal scope of the research question. For the remaining sensitive parameters, more precise estimates can be obtained empirically, which will reduce their sensitivities.

The choice of statistical distribution for future emissions, TH, and building lifetime are explored further in the supplementary material of Paper V:

Choice of statistical distribution for future events: The chi-square distribution and normal distribution with time-dependent variance are found most fit. Integer numbers of replacements should be avoided since they will lead to abrupt changes in results when material and building lifetimes change, and fractional numbers will underestimate replacement emissions. The importance of choosing an appropriate distribution is especially important if dynamic effects are not considered or under long THs.

Time horizon: The A-phase is independent of TH. Longer THs lead to higher emissions from the B-phase as long as the building lifetime is longer than the TH. The importance of the C-phase increases for THs longer than building lifetime.

Building lifetime: In general, shorter lifetimes lead to lower impact from the B-phase and higher impacts from the C-phase. The A-phase is independent of building lifetime, while the B- and C-phases greatly depend on it in long THs. Building lifetime is an unknowable parameter, and under long THs it contributes to large uncertainty in the results of the future lifecycle phases, while its contribution to uncertainty is greatly reduced with shorter THs.

Reduced importance of building lifetime. In Norway it is common practice in some research communities as well as in standards and consultancy to carry out carbon footprint assessments of buildings with a fixed 60 year lifetime. That number is rather arbitrary and not based on empirical building lifetimes. Other countries have similar conventions, although the exact lifetime may vary. In literature, 125 years [48; 49] and 140 years [41] have been used for buildings in Scandinavian countries; much longer than the commonly used 60 years. However, a distinction should be made between the building lifetime and the analysis period. The building lifetime determines for how long replacement emissions take place and the timing of the end-of-life phase of the building. The analysis period, also called the time horizon, determines the cut-off year of emissions in the assessment, and thus determines the last year of climate change impacts that is of interest for the particular assessment. This is an important distinction that has beneficial implications in conjunction with the effects of delayed emissions. The building lifetime becomes less influential when the effect of delayed emissions is accounted for, along with the lesser importance of all future emissions. A clearly defined time horizon is therefore a better cut-off for future impacts than an arbitrary building lifetime. Instead of relying on artificial conventions for building lifetimes, one can agree on for example a 100 year time horizon on the climate change effects. The building can then be assumed to stand for a minimum of 100 years, with multiple renovations. The further into the future *emissions* occur, the less *climate impact* will occur during the time horizon. In year 100 and onward, no climate impact will be accounted for since it does not happen within the time horizon. The assumption of a lifetime longer than the time horizon has the implication that demolition activities will not occur during the analysis period. These activities, however, account for a small fraction of lifecycle emissions, and since they occur far into the future, their climate impact is even further reduced. Emissions from demolition activities can in such cases be neglected while emissions from end-of-life treatment of the materials replaced during the time horizon are still included.

The building lifetime is also responsible for another important uncertainty. Results from building LCAs is usually reported per floor area of the building, but is often also divided by the lifetime of the building to get the average yearly emissions. This will deflate the near term emissions from material use and distribute them equally over the building lifetime. Dividing by lifetime introduces an unnecessary additional complexity and it is better to keep the models as simple as possible to faithfully represent reality and limit uncertainties. Carefully performing the LCA and then dividing by a highly uncertain number is not wise, except for rare cases where the building lifetime is an integral part of a comparison between buildings designed for different lifetimes. In those cases, explicit reasoning should be given for the differences in the chosen lifetimes and the involved uncertainties should be clearly expressed. In the vast majority of cases though, one can avoid the uncertainties related to building lifetimes by agreeing on specific time horizons to be used.

Chapter 5

Conclusions

The climate change impact of material use in buildings lacks consistency in inventory modeling, system boundaries, and calculation methods used. Such LCA studies are victim of large uncertainties and are highly sensitive to model parameters. Furthermore, these impacts happen over periods of many decades, but highly influential time-dependent effects are nevertheless usually not considered. The mentioned difficulties mean that comparing studies is challenging, which makes it difficult to establish reliable reference values that can be used to benchmark climate change impact performance. In all project phases, but especially the planning and design phases, data availability is a major limitation.

This thesis proposes a framework for climate change impact estimation of material use in buildings. Data from previous LCA studies of buildings are stored in a structured database specifically tailored for the purpose, which ensures transparency and consistency, and makes it possible to make use of the data in statistical applications. The system boundary of the material inventory can be improved by the use of relevant data from other case studies in the database. The system boundary of emission sources was also expanded by proposed methods to account for waste incineration and of biogenic carbon sequestration and carbonation of cement products. Various other methodological novelties were also presented. To generate useful statistical embodied emission information, a set of embodied emission metrics for building subparts were introduced. Time dependent effects, such as technological developments and delayed emissions were modeled. A framework for making use of the data from previous case studies throughout the planning phases was suggested. The methods were demonstrated by recalculating previous LCA studies with these improved methods, and statistical benchmarking results were presented.

These findings contribute to advancing estimation of climate change impacts of material use in buildings. The completeness of such assessments is increased by widened and more consistent system boundaries, and the quantification of effects is improved by the proposed methods. With increased comparability of case studies comes higher relevancy of results and more reliable benchmarks. As a combined consequence of these, uncertainty is reduced significantly, and policy-relevancy is drastically improved. The presented statistical results of emission profiles of building types can potentially be used to benchmark future building LCAs and in policy.

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Part B

Main publications

Paper I

A Database Tool for Systematic Analysis of Embodied Emissions in Buildings and Neighborhoods

Eirik Resch, Inger Andresen

Published in *Buildings*, MDPI

The paper's context in the thesis:

Details a database structure for organizing and storing previously conducted building LCA studies, to leverage past data for future applications. Use cases exemplified with statistical results.

buildings

MDPI

Article

A Database Tool for Systematic Analysis of Embodied Emissions in Buildings and Neighborhoods

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Abstract: There is a growing body of research on the embodied emissions of individual buildings, but the results and methods remain mostly inaccessible and incomparable due to insufficient reported information, and differences in system boundaries, methods, and data used. This inhibits further utilization of the results in statistical applications and makes interpretation and validation of results difficult. The database tool presented in this paper attempts to mitigate these challenges by systematizing and storing all relevant information for these studies in a compatible format. The tool enables comparison of results across system boundaries, improves the transparency and reproducibility of the assessments, and makes utilization of the results in statistical applications possible. Statistical applications include embodied emission benchmarking, identifying emission drivers, and quantifying relationships between variables. Other applications of the tool include the assessment of embodied emissions of buildings and neighborhoods. This paper presents the tool and exemplifies its use with preliminary results based on a dataset of 11 buildings. Work is ongoing to expand the dataset, which will provide more comprehensive results.

Keywords: life cycle assessment; embodied emissions; carbon footprint; benchmark; comparative analysis; reproducibility; reporting; validation

1. Introduction

The building sector continues to be among the main sectors worldwide responsible for greenhouse gas emissions. Most of these emissions are caused by operational energy use in existing buildings, but new constructions, which is the focus of this paper, also make a considerable contribution in the form of emissions from the construction materials and related processes [1]. In recent years, modern building energy codes for new constructions are pushing operational emissions toward zero. Meanwhile, the relative share of life-cycle emissions for these buildings gets shifted from the operational emissions to the production and transportation of building materials and other emissions related to the construction, maintenance, and end-of-life processes; the emissions that are often referred to as embodied emissions. A building's life-cycle impact on climate change is normally estimated with life cycle assessment (LCA) methodology and the impact category global warming potential (GWP) with units kgCO_2e. [2]. The results are often normalized by a floor area metric and by lifetime, to get comparable results.

When assessing the embodied emissions, different buildings may end up with similar results on the whole building level but for very different reasons. To identify the factors responsible for GWP impact, a high resolution on emission results and detailed information on study design and parameter values are prerequisites. Without this information readily accessible, it is impossible to know if the results are mainly affected by design and construction choices, or by the study design itself. In practice, however, such study results are mostly reported with low resolution and rarely with sufficient details about data used, system boundaries, calculation methods, or other information [3,4] crucial for evaluating the validity of the assessment. Such details are also needed for making use of the results for comparisons and statistical applications that may greatly benefit the efforts to reduce the carbon footprint of buildings.

In the LCA methodology, the product system is modeled by one of the three life cycle inventory (LCI) techniques: process analysis, environmentally extended input-output analysis (EEIOA), and hybrid analysis, which can lead to fundamentally different results. In process analysis the product system is broken down into the individual processes in the products life cycle, thus compiling an inventory of specific production processes. This allows for high accuracy by the use of product specific data, but the method has systemic incompleteness. Alternatively, EEIOA applies macroeconomic figures to assess the environmental flows, which allows for a systemically complete representation but relies on aggregated economic data. Combining the two previous approaches results in a variety of methods known as hybrid analysis which attempts to tackle these problems [5]. The embodied energy has been found to be 3.92 times higher on average in studies using hybrid analysis compared to studies using process analysis [6]. Although process analysis is known to suffer from the so-called truncation error, which has been shown to greatly underestimate the embodied environmental impacts of buildings [6–8], it is the most widely used LCI technique, and thus the potential for statistical analysis is greatest for process analysis.

Many similar but slightly alternative approaches to building LCA are practiced today, which can lead to very different results [9–11]. In a recent review article on the embodied energy of buildings, it is pointed out that previous embodied energy studies show considerable variation in reported values, owing both to methodological parameters such as differences in system boundary, calculation method, and energy units, as well as to data quality issues of parameters such as incompleteness, inaccuracy, and non-representativeness [11]. In another literature review from 2010 of 20 journal articles [3], the embodied energy in the assembly phase was found to range from 2 to 72 years equivalent of annual operational energy (embodied energy to total life cycle energy ranged from 2 to 51%), thus emphasizing the large spread in results. The study found that most of the journal articles that describe LCA of buildings are not providing sufficient documentation to be useful for comparison. In particular, unit processes and calculation procedures are rarely stated. In a similar study from 2013 [4], where 206 cases were compared, variation of which life cycle stages were included, and arbitrary building lifetimes were put forward as comparability issues. Moreover, the authors emphasized the difficulty of comparing the studies due to lack of documentation and inconsistency in methodology. The missing information included which life cycle stages and sub-stages are included; whether primary or delivered energy is used; building area and area units; general description of the building such as location, use, and number of stories; features that would affect embodied energy such as structure type, wall, roof, floor, and windows; and features that would affect operational energy such as insulation levels, and type of energy used for heating and cooling. Although these studies concerned embodied energy, the methodology is similar for emissions. In buildings where operational energy efficiency has been given high priority, the fraction of embodied material emissions alone have been found in some cases to be as much as 75% of total emissions (3–6 $kgCO_2e./m^2/year$), as shown in one comparative study [12], and 87% (6–21 $kgCO_2e./m^2/year$), as shown in another [13]. This shift from operational to embodied emissions is due to lower operational energy consumption but also due to different/more material use [14]. In terms of life cycle energy, low-energy buildings have lower total lifecycle energy demand but an increased embodied energy [6,15,16]. The embodied energy from supplementary insulation will at some insulation level no longer be offset by thermal operational energy savings. One study using a hybrid approach found this threshold to be just above the current minimum energy efficiency requirement in Australia [17]. The time at which emissions occur is also of relevance; a spike in short-term embodied emissions may be more damaging than emissions from future energy use because the decay of carbon in the atmosphere is relatively slow and future emissions intensities are more uncertain when considering technological advancements [14,18].

Furthermore, limitations of data quality and difficulties to assess uncertainty are acknowledged problems in LCA [19], and uncertainty analyses are not included in most studies [20]. Björklund [20] listed different types of uncertainties appearing in LCA models, and ways to improve on this using uncertainty and sensitivity analyses. Khasreen et al. [21] similarly highlighted the need for an internationally accepted framework, protocol, and conversion tools to improve comparability of building LCAs, as well as transparency and higher accuracy of data sets. Among the LCAs that were investigated, they concluded that "there are no two studies which could be directly compared, due to differences in goal and scope of the study, methodologies used to achieve these different goals, and data used."

Traditional LCA methods are time-consuming and have to be specifically tailored to individual buildings [21], with a need for large amounts of high-quality data for the specific building in question to make an accurate prediction. Even with all the necessary data available, differences in system boundary from project to project make them almost impossible to compare directly, and little can be stated about the uncertainties of individual analyses without extensive investigations. On a neighborhood scale, where complexity increases further, there is little knowledge, methods, and tools available to assess the embodied emissions, especially in an early stage [9].

To compare LCAs with varying system boundaries, the results need to be stored with the highest available resolution for all building parts and materials, as well as for the lifecycle stages. In Norway, several embodied emission analyses of buildings have recently been performed in accordance with international and national standards such as NS-EN 15978 [22] (LCA calculation method) and NS 3451 Table of building elements [23] (building parts classification), making them more fit for comparison. To compare the LCA studies, systematic decomposition and classification of the buildings and their elements are needed; first, by categorizing the buildings by attributes such as physical dimensions, typology etc., and then, through a decomposition of the physical building parts, with an increasing level of detail according to NS 3451. A building has walls, roof, floors, foundation etc. that again consists of load-bearing and non-load bearing walls, windows and doors, and so on. In turn, each of these building parts is made up of a set of building materials and components that are bought from a manufacturer. Each of these materials' and building components' emission values is dependent on the system boundaries used for their individual lifecycles and the lifecycle of the building. When comparing study results, the comparison must be based on the same lifecycle phases and building elements; results for each lifecycle phase must, therefore, be stored for all building parts.

Several previous studies have characterized embodied emissions and embodied energy by a breakdown of a building into its sub-elements. For example, by a separation of buildings into "envelope," "structure," "finishings," etc. [24], or by a hierarchical characterization that further splits "structure" into sub-elements such as "foundations," "columns," "beams," and "slabs" and splits "envelope" into "outer walls," "windows," and "roof" [25]. Early phase parametric LCA approaches such as the one presented in [16] are also dependent on a breakdown of buildings into sub-elements. However, as far as the authors are aware, a hierarchical model of building elements that encompass the entire building and its life-cycle stages and applies this for characterizing LCA results has not previously been presented in the literature.

This study presents a relational database tool that aims to systematize result data and study design for building LCAs. By systematically organizing studies of embodied emissions in buildings, the tool ensures accessible, comparable, and more reliable data. Accessible and reliable data are the foundation for many useful applications. The building LCA database tool (bLCAd-tool) can be used for applications such as benchmarking, comparative analysis, predictive statistics, LCA of neighborhoods and individual buildings, and transparent reporting. It allows for LCA results at different resolutions and across different system boundaries to be entered into the database and enables easy access to this data by restricting the output of data from the database to the studies that comply to some user-defined criteria. Consequently, because the data are made accessible and compatible, the utility of the existing data increases. The limitations of current practice described above call for a unified framework for systematically handling the data related to embodied emissions of buildings so that it can be applied in various decision-making processes related to climate change mitigation. Benchmark values for embodied emissions may soon become part of building code requirements [26]. Furthermore, there is a need for decision support and simplified assessments in the early design stages of building and neighborhood projects, since the early design stages are when most influence toward emission reduction can be achieved. In the following, the tool is presented in Section 2 and some selected applications are demonstrated in Section 3. Thereafter follows a discussion in Section 4 and finally a conclusion.

2. Materials and Methods

This section first describes the structure of the database, then describes the handling of the data and the calculation method. Thereafter follows a description of the data used in the statistical analysis in this paper.

2.1. Database Design

The building LCA database-tool (bLCAd-tool) is a relational MySQL database that can store results from existing, and calculate new, process-based life cycle assessments of buildings. It is designed to apply this data for the analytical purposes described in the introduction. The Entity-Relationship-Diagram (ERD) for the database design is shown in Figure A1 in the appendix. The database has three main components: a "building" component for storing attributional data about the building and study, a "material: component for storing information about the materials and products that make up the building, and a "results and inventory" component with modules for storing, calculating, and aggregating LCA results for the building. These three components contain information related to distinct parts of an LCA: the material component contains the background data on the unit processes used in the individual studies, serving a function similar to databases such as Ecoinvent [27]; the results and inventory component is calculating and storing the GWP results for each building element and inventory; and the building component classifies the buildings and the studies, with information relevant for interpreting the results. The information stored in these components are listed in Figure 1.

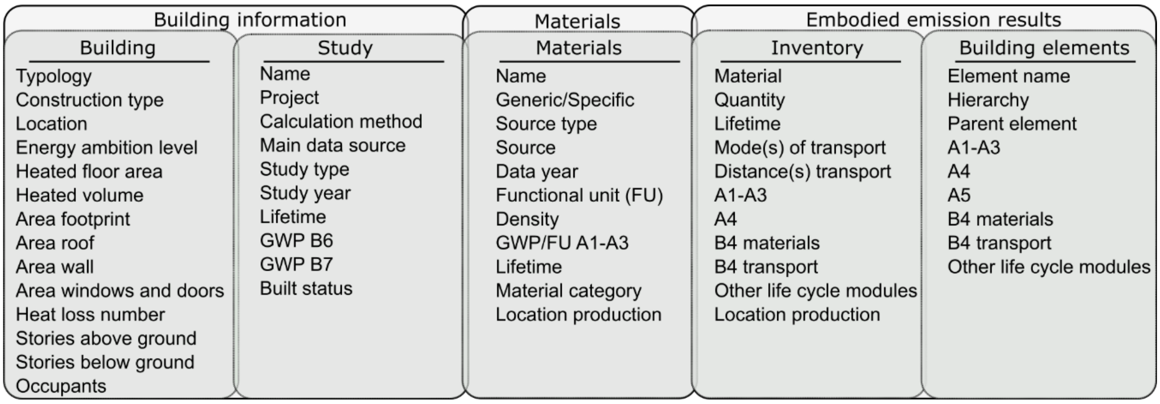


Figure 1. The main information stored in the three components of the database.

The building component contains attributional information specific to the building and the study related to that building. Building information includes typology, construction type, location, energy ambition level, floor area, surface areas and volume, stories (above and below ground), and heat loss number, in addition to the number of occupants. The number of occupants in a building allows for a representation of embodied emissions per capita, which can be useful when comparing lifestyles or the area provided to fulfill functions such as housing and workplaces. Since larger houses in general are more energy efficient per m^2, embodied emissions per capita can be an important additional metric [28]. Study information includes the calculation method, main data source (e.g., EPD), study type (e.g., scientific), year of assessment, study lifetime period, the built-status (e.g., design phase/as-built phase), and the yearly GHG emissions results from the operational phase of the building (life cycle module B6 and B7).

The materials component is independent of the buildings and stores information about materials and products, including source and emission data. These materials are the per unit GWP background data that was used in each study. This background data is typically sourced from LCA databases such as Ecoinvent, or from Environmental Product Declarations (EPDs), where the sources used are either Generic or Specific, i.e., average emission values for a typical representative product, or emission values from a specific supplier, respectively. Both the location of production and the lifetime of the material (reference service life (RSL)) can be stored for each material and for each inventory entry. This is because those parameters can come either together with the background data, or they can be set by the LCA practitioner if the background data are used as a proxy for the actual materials used in the building. The lifetimes of the materials are also highly dependent on their use case and must therefore often be set specifically for each material inventory.

The third component, whose structure is illustrated in Figure 2, consists of the building elements and the material inventory. Each building has GWP results from an LCA connected to it. These results are stored in a hierarchical building elements tree-structure, where the total result for the whole building is at the top level, with sub-elements that have increasing resolutions. This hierarchical structure is organized according to the Norwegian standard NS 3451 Table of building elements [23], which has three sub-levels. This standard is widely used in the Norwegian context for assessing quantities, costs, and LCA organization of buildings. However, the tool is built for flexibility, and switching to a different category structure is trivial. These building elements are in turn optionally connected to material inventory entries, where each entry is associated with a material and include quantity, lifetime, transport distances and modes, and location of production. Furthermore, the emissions for each material inventory entry are calculated and stored in that entry.

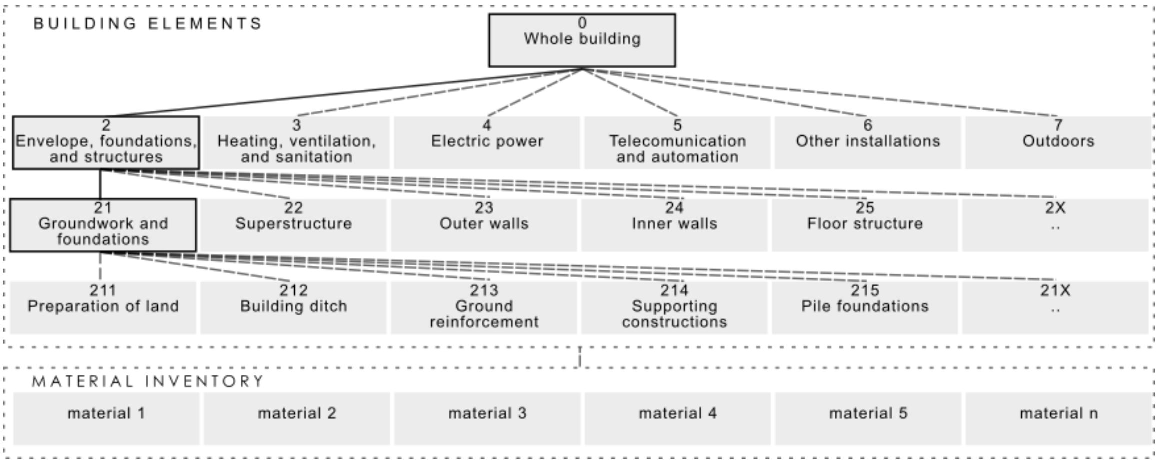


Figure 2. The hierarchical structure of the building elements according to NS 3451, and the material inventory. The elements with bold outlines are expanded to show their sub-elements. Each building element has its level ID above its name. The inventory items are connected to specified building elements.

Published research and other acquired study results come with varying data detail level. To be able to make use of these results regardless of the building element level at which they are reported, results can be added on a freely chosen level of resolution. Higher levels will be automatically calculated based on lower-level aggregation. Results with higher resolution reveal more information about where emissions arise and about study design. Consequently, a higher resolution is preferred but is not always available. To accommodate varying resolutions, there are two ways of entering GWP results: (1) entering results values directly into a chosen building element hierarchy level, or (2) entering material inventory data. The second option, which has the highest level of detail, involves selecting a material from the materials component, followed by entering material quantities, transport distances, and the expected service life of the materials. The material inventory entry will be associated with a chosen building element and building elements on all levels will subsequently be automatically calculated based on lower level aggregation. This last option is equivalent to conducting the LCA calculations from scratch and can also be used for this purpose.

In each case, the parent building elements are calculated as the sum of its subentries (where there exists any). If there are entries in the material inventory for a given building element, the material inventory emissions will overwrite any manually entered values in the building elements for that lifecycle phase. Likewise, if a value is entered into a building element, any values entered into a parent level of this building element will be overwritten for that lifecycle phase. In this way, entries on lower levels (higher resolution) have priority in the calculations and will overwrite entries on higher levels (lower resolution).

Results from building entries in the database may then be extracted with SQL queries, restricting the output to a chosen set of buildings, building elements, life cycle phases, inventories, and materials from studies that comply to some chosen set of parameters/criteria. In this way, the organization of the database makes it straightforward to query results and conduct analyses on the subset of entries where the chosen parameters/criteria apply.

2.2. Data Handling and Calculations Methodology

An emphasis has been put on making most data optional since data availability among building LCAs is a major concern. Although a full dataset is preferred, the lack of certain data should not exclude a building from being part of the database. Therefore, most attributional building data are optional. The same is true for materials. Likewise, a study can include a chosen selection of life cycle phases for the GWP results. These are organized according to the widely used European standard EN 15978 [22] for life cycle assessment, which separates emissions into lifecycle modules A–D. However, most studies are using much narrower system boundaries, and many modules cannot be computed directly based on available data. This version of the database tool is, therefore, focusing on the life cycle modules that are most often observed in building LCAs, namely A1–A3 (material production), A4 (transportation to the building site), and B4 (material replacements throughout study lifetime period), which all can be calculated based on basic inputs. In addition, there is an option to manually enter emissions for the modules A5, B1, B2, B3, B5, C1, C2, C3, C4, D1, D2, D3, and D4 into the inventory entries and the building elements. The two remaining modules, B6 (operational energy use) and B7 (operational water use), are covered on the whole building level and are therefore stored in the buildings component. The minimum requirement for manually entered results is that they are separated into life cycle phases.

The LCA calculation method has two parts: first, the emissions from each material inventory are calculated from material emission factors, quantities, distances, etc., and then an aggregation of the inventory emissions is carried on through the building parts hierarchy.

If material inventory data exist, the GWP in the material inventory is calculated for the three phases A1–A3, A4, and B4. Module A1–A3 is the product of the unitary GWP emission factor for the material and the quantity of that material. Module A4 is the sum of emissions from up to three transportation modes, where each is calculated as the product of the emission intensity of the mode, the weight of the material, and the distance. Module B4 is calculated as the fractional number of replacements needed for that material throughout the study lifetime period, based on the estimated lifetime of the material which is provided as input. The transportation of these future materials to the building site is also calculated (in the same way as A4) and stored separately from the materials part. The building elements are then calculated as described in the section above.

The database is designed for flexibility and future needs, in that, categorical data can easily be altered and added by changing the rows of tables. The tool has been designed to detect and avoid several systematic errors, such as unit inconsistency, incorrect data entries, and similar, by controlling them before they are entered into the database. In addition, the tool benefits from the comprehensive error checking built into the MySQL language on which the database is based, which ensures data relations are correct when entering, altering, and deleting entries and prevents duplicate entries and incorrect data types.

2.3. Data Collection and Application

During a data collection period, 11 studies were acquired from various sources. Of these, five are from the Research Centre on Zero Emission Buildings [29], and six are from two consultancy firms. All building projects are situated in Norway, where nine have been built, and two are concept buildings. Seven have full inventories entered into the database, while for the rest the results are entered at varying building element levels. There are three single-family residential buildings, two office buildings, five school buildings, and a swimming arena, all of which are designed with the goal of low lifecycle emissions. The buildings are in the following denoted by a letter (O: office, R: residential, S: school, SW: swimming arena) and a number, e.g., O1. The LCA calculation method applied in the collected studies was standardized and carried on to the calculation method in the bLCAd-tool which is described above.

3. Results

The building LCA database tool (bLCAd-tool) presented in this paper is designed to improve the transparency and reproducibility of embodied emission assessments of buildings by systematizing reporting, storing, and calculation procedures. This unified framework for systematically handling the data related to embodied emissions can, as already mentioned, be applied in various research and decision-making processes related to climate change mitigation. Some selected applications of the tool are presented and exemplified in this section. The capabilities of the tool presented in this section are

- Transparent reporting of study results;
- Comparing study results;
- Benchmarking embodied emissions;
- Exploring relationships between emissions and attributes;
- The contribution from various building material categories;
- Analyzing embodied emissions of neighborhoods.

3.1. Transparent Reporting

All data used in the studies are stored together with full resolution emission results and can also include detailed information about the building and study. Ideally, all this information should be made available for validation, replication, and further utilization of the results. In the cases where it is not, it should be specified what information is not available. Table 1 lists the information that can be reported with the bLCAd-tool (refer to Figure 1 or Figure A1 for more details). The tool makes it straightforward to report this information in different formats such as csv, xml, json, sql, and html. This is done with an option for exporting entire tables or query results, where the query results can be any chosen composition of that information.

Table 1. The information that is stored in and can be reported by the bLCAd-tool. Detailed contents are listed in Figures 1 and A1.

Category	Stored Information
Building	General information about the building as well as morphological parameters.
Study	Information about the study such as calculation method, year, and lifetime.
Materials	Information about all the materials such as GWP per unit, source, data type.
Inventory	The quantities of each material, the transport distance, lifetime, GWP results.
Results	Emission results for each building element and for each life cycle phase.

3.2. Comparing Study Results

The storage of emission results at a detailed resolution of building elements, and across life cycle stages, allows for comparison of multiple studies. While aggregated results are problematic to compare due to differences in system boundaries, results of individual life cycle stages for a certain building element allows for more representative comparisons.

Furthermore, the functional units (functions that are to be fulfilled by the buildings) vary (i.e., office/residential), and so does the requirements to obtain those functions (i.e., climate). Thus, grouping study results by building characteristics such as typology, geography, and energy ambition level, and then normalizing by morphological parameters such as areas and volumes, increase the validity of the comparisons. Figure 3 shows the emissions attributed to material production (A1–A3) and replacements (B4) from the building element category labeled “Envelope, foundation, and structure” for 11 buildings, separated into sub-building elements. The emissions are normalized by each building’s heated floor area and a 60-year lifetime and are grouped by the typologies office, single-family residential, school, and swimming hall. All the buildings are designed for the Norwegian climate and all had the ambition of reducing embodied emissions.

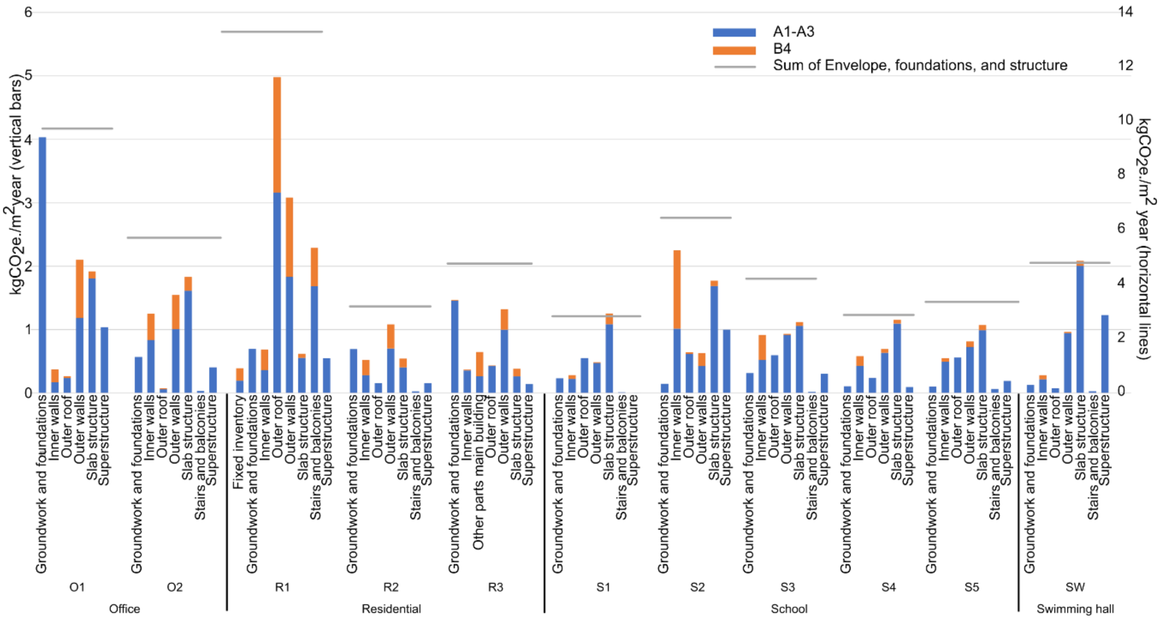
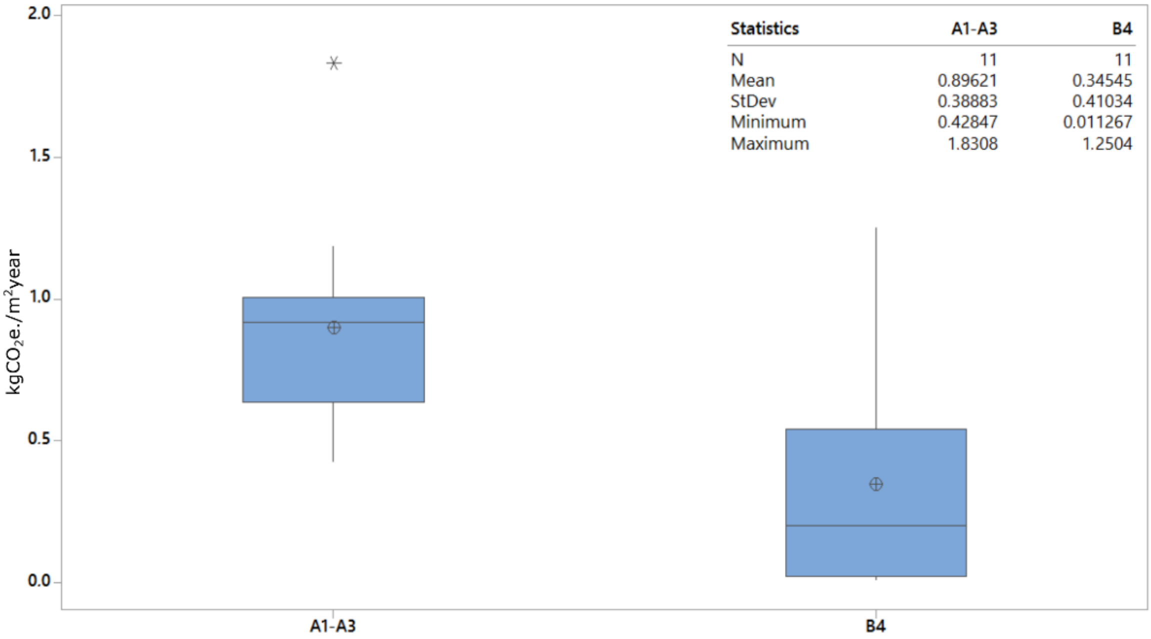


Figure 3. The embodied emissions in kgCO$_2$e./m^{2}year from material production (A1–A3) and replacements (B4) for 11 buildings from four different typologies. The building elements in the category “Envelope, foundation, and structure” are shown for each building (left axis) together with the total for this building element (right axis).

Although the total emissions for “Envelope, foundation, and structure” are similar for some of the buildings, increasing the resolution of the results shows that there is large variation in how the emissions are distributed across sub-elements and life cycle phases, thus emphasizing the importance of adequate resolution when comparing study results.

3.3. Benchmarking Embodied Emissions

One way to establish embodied emission benchmark values is to base them on statistics from current industry practice. Although the current dataset used in this analysis is not sufficiently large for representative benchmarks on detailed building element levels, it is a first step toward practically useful benchmarks. With high-resolution results from a sufficient amount of representative buildings, embodied emission values can be standardized and used as benchmarks that other building projects can be compared against. In the same way as described above for comparing results, the buildings should also here be separated by their functions. This will make the benchmarks representative for specific typologies, geographies, etc. Likewise, emissions for each building element is dependent on different factors, some that can, and others that cannot be easily influenced during the design and construction phases of a building project. For example, the groundwork and foundation are dependent on the ground conditions at the site, which cannot easily be influenced, and the weight the foundation must be able to carry, which can be influenced by e.g., the building height and construction type. Ideally, benchmarks could be established based on such conditions for every building element. However, this implies a sufficient amount of data on these resolutions. When reliable benchmarks are available, building projects can use them as a frame of reference both on the building, building-element, and inventory level individually for each life cycle phase. Figure 4 shows an example of the distribution of the embodied emissions per floor area and lifetime for the building element "Outer walls," including all buildings in the database.

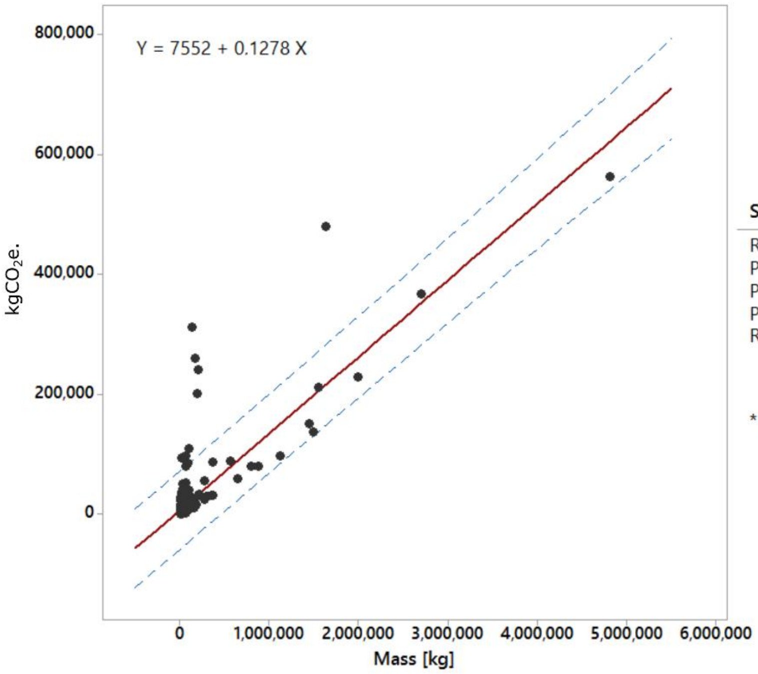


Statistics	A1-A3	B4
N	11	11
Mean	0.89621	0.34545
StDev	0.38883	0.41034
Minimum	0.42847	0.011267
Maximum	1.8308	1.2504

Figure 4. The distribution of embodied emissions per floor area and a lifetime of 60 years for the outer walls of the 11 buildings (kgCO_2e./m^2year).

3.4. Exploring Relationships between Emissions and Attributes

There are many factors that affect the embodied emissions of buildings. The relationships between variables in the database and the resulting emissions can be explored with statistical methods. Examples of such relationships are how the emissions of building elements (e.g., outer walls) relate to corresponding areas (e.g., outer wall area), how emissions from the foundation relate to the weight of the building, or how well the total quantities of different materials (e.g., metals, timber) can predict their corresponding emissions. The weight of each material inventory entry is another such variable. In Figure 5, the weight of the items in the inventory of the database is plotted against the emissions from life cycle phase A1–A3. The relationship between the two variables is explored through a regression model that, for such a simple model, has relatively high predictive power. This example was chosen because the inventory dataset in the database had a sufficient size ($n = 326$). One outlier was removed, which related to an unusually large amount of concrete ground reinforcement. The data points in the figure are unevenly distributed but serves to demonstrate the purpose. With a more complete dataset, more complex relationships with multiple explanatory variables such as building attributes, material categories, etc., as described above can be explored.



Statistics	Selected Model Linear
R-squared (adjusted)	67.73%
P-value, model	0.000*
P-value, linear term	0.000*
P-value, quadratic term	—
Residual standard deviation	33140.662

* *Statistically significant ($p < 0.05$)*

Figure 5. The weight of all inventory items plotted against emissions from material production (A1–A3) in kgCO$_2$e., together with a regression model of the correlation. One outlier which is related to a special case of ground reinforcement was removed.

3.5. Contribution from Building Materials

In addition to emissions from building elements, practitioners should also be aware of which materials and components that normally have the highest carbon footprint. This is useful in the design phase when making choices between construction types and materials, and during the construction phase to reduce waste. The lifetimes of the materials and components are important, since choosing long-lasting products is an effective way of reducing the lifecycle carbon footprint. Figure 6 shows the ten types of material groups within each typology that on average have the largest embodied emissions from their production per floor area, for the building element "Envelope, foundation, and structure," based on the buildings collected in this study. A1–A3 shows the initial emissions, while B4 shows emissions from replacements needed over a 60-year period. Alternative materials or materials from clean manufacturers should be considered for material groups with high impact from A1–A3. Long-lasting products should be sought after for material groups with high impact from B4.

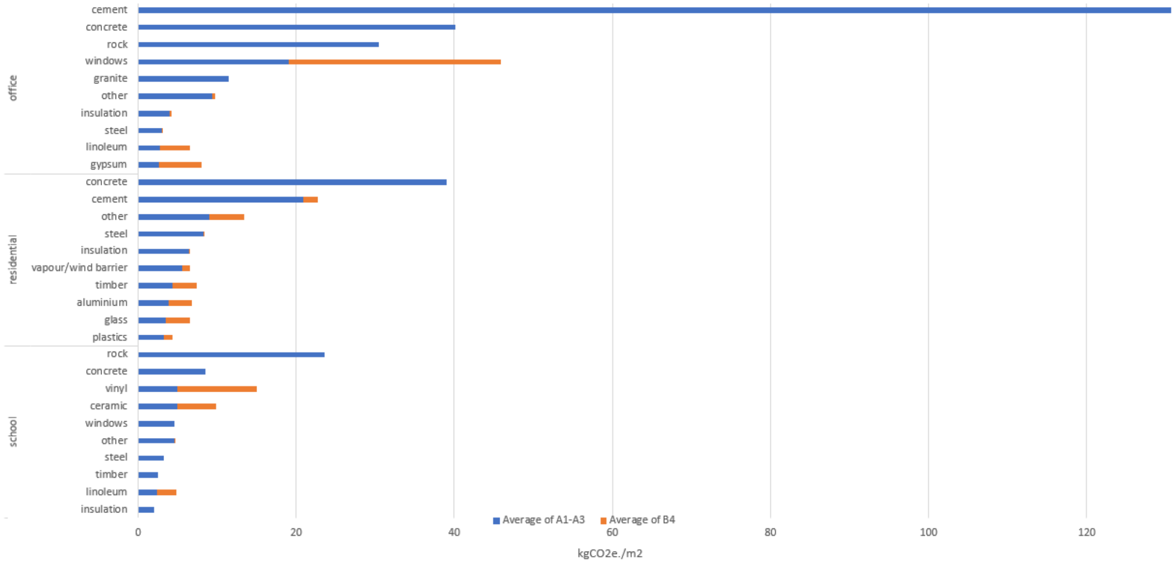


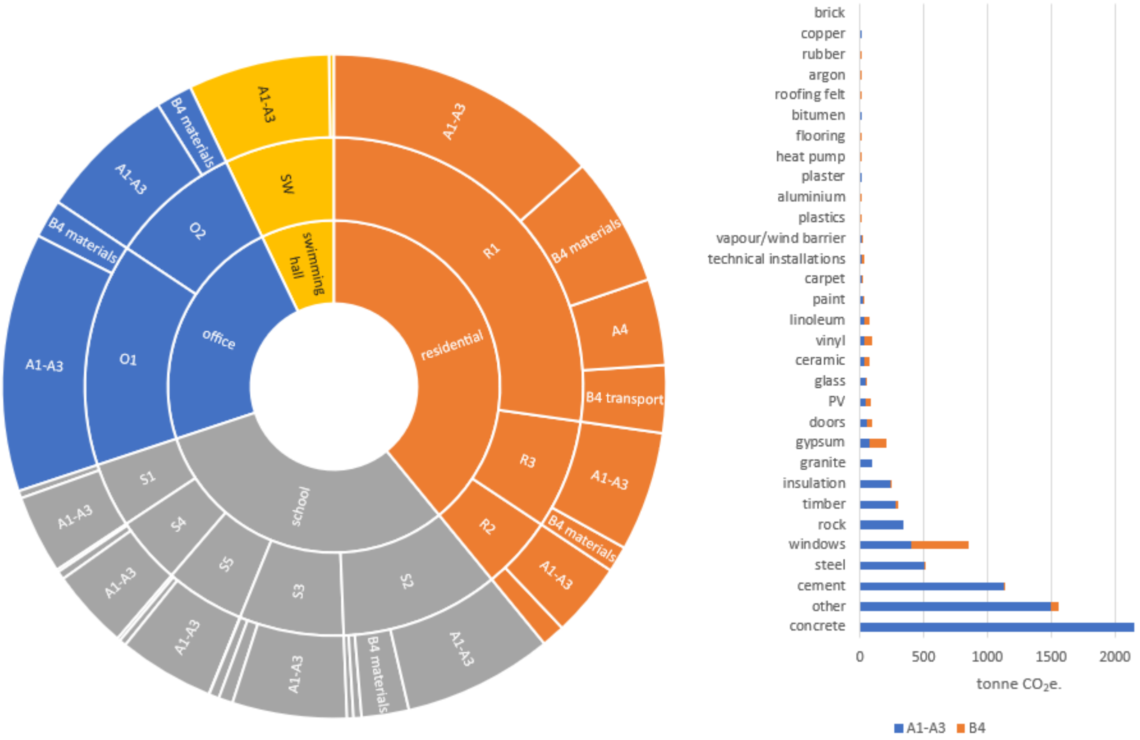
Figure 6. The ten material groups with the largest average contributions to production emissions per floor area for three typologies from the building element "Envelope, foundation, and structure."

3.6. Embodied Emissions of Neighborhoods

One of the important components of neighborhoods in terms of emissions are the buildings, while other components include infrastructure, roads, open spaces and public areas, and the transportation system. In the present version of the bLCAd-tool, the focus is on the buildings. The tool can be further developed so that neighborhood objects other than buildings, such as roads and infrastructure, vehicles, public spaces, and more, can be included.

In an LCA of a whole neighborhood, the data rapidly becomes very complex. The standard solution to reduce this complexity would be to aggregate the results for each building. However, this reduction of resolution reduces the usefulness of the results. The advantage of a tool such as the bLCAd-tool in a neighborhood application setting is that all buildings in the neighborhood are stored together with full results and data source resolution and are compatible. Information about the buildings, GWP results, materials, and data sources can thus easily be compiled in any preferred composition, and analysis can be directly performed. The functions served by the neighborhood such as total housing, workplace, school, and kindergarten floor areas and volumes can easily be extracted. The total roof area is available for solar potential estimation. The aggregated heat loss number for the whole neighborhood can be calculated, and the simplified total annual emissions from the operation are available for different energy standards. Furthermore, the embodied emissions for all buildings can be simultaneously investigated, such as the emissions associated with individual building parts or emissions from transportation of materials to the construction site and how it relates to the distances to the production sites. Materials can also be analyzed at the neighborhood level, based on quantities, material categories, and emission factors. In cases where material inventories are not available for a building, estimates based on the other buildings can be used as a proxy for its embodied emissions.

Some development projects have a stated goal of becoming a "Zero Emission Neighborhood" by offsetting embodied emissions with renewable energy production on-site so that the net emissions reach zero over a set study period. As this "carbon budget" includes the whole neighborhood rather than individual buildings, it is beneficial to have aggregated numbers easily available. The bLCAd-tool can be used to analyze such an area. As an example, the data from the buildings in the current database have been used to demonstrate the application of such an analysis on the neighborhood level. The distribution of emissions across typologies, buildings, and the life cycle phases included in each study are shown in Figure 7a, which shows the distribution of emissions for a thought neighborhood setting with the buildings in the database. Figure 7b shows emissions from material production in initial construction (A1–A3) and replacements (B4) grouped by material group, which can be used to determine the largest potential for emission reduction.



(**a**) (**b**)

Figure 7. Example of how the distribution of emissions in a planned neighborhood could look like: (**a**) How the emissions for all buildings are distributed across typologies (inner circle), buildings (middle circle), and the life cycle phases included in each building study (outer circle); (**b**) The material groups that contribute the most to the overall emissions in A1–A3 and B4 (for all buildings with inventory) and thus where the largest potential for reduction in these life cycles lies. The buildings used here are not connected to an actual neighborhood; they are merely used as examples.

4. Discussion

This paper has presented a database tool that systematizes embodied emission assessments of buildings by characterizing buildings as a hierarchical set of building elements, themselves composed of materials, to offer a high-resolution breakdown of their embodied emissions. In addition, the emissions are separated into lifecycle stages according to the European EN 15978 standard. Using this approach on a number of buildings will help produce systematic data that can then be used in statistical analysis to produce more reliable embodied emissions figures. Such applications were then demonstrated based on 11 previously conducted LCAs of Norwegian buildings. This systematization helps address the current inconsistency in reporting embodied environmental flows of buildings.

The characterization of emissions follows a logical structure based on adopted standards. The hierarchical structure of building elements is based on the Norwegian standard NS 3451 which by no means is the only way to perform such a breakdown. It is suitable in the setting of this study since the collected LCAs conform to this standard, however, alternative categories might be better suited for other geographical regions or other contexts. The hierarchical categories can easily be altered and are likely to be developed to suit different needs in the future, among them the inclusion of infrastructure to model neighborhoods. The breakdown of the lifecycle stages is done in accordance with EN 15978, where all modules A–D are implemented. Although many of these modules are excluded in most LCA studies, there is a possibility to include them in cases where this data exists.

Although previous studies have adopted a similar logic of a breakdown of a building's environmental flows into sub-elements and life cycle stages [16,24,25], as far as the authors are aware, no such database model for a complete characterization of all building elements and life cycle stages has previously been presented. In particular, in contrast to previous studies, the database model presented here has a focus on standardization and integration of existing studies into a common format to increase consistency and comparability.

Going forward, an extension of the model to include infrastructure is necessary to realistically model neighborhoods. This will be achieved by extending the hierarchical structure of building elements to also include the remaining neighborhood elements. In addition, the database component for storing building information must be extended to also include information on the infrastructure.

The SQL database used in this paper is a relational database that in addition to storing entered data also stores empty fields where data is not available. Considering the incompleteness of LCA data the proportion of empty fields is notable. Currently this is not a problem since the number of studies collected is limited, however, if the amount of studies increases significantly, a non-relational database may be considered as to save memory and increase performance.

The current database tool is able to store process-based LCAs while input-output and hybrid LCAs are outside the scope of this work. Most studies to date are applying the process-based LCI technique; the database thus has a large potential to utilize this pool of existing studies and future studies applying this technique. However, since process analysis is known to underestimate results, future work should consider an additional integration of the other LCI techniques. Such an integration of hybrid analysis can be made possible by the inclusion of the cost of materials and input-output based environmental impacts of materials and processes.

Life cycle assessment involves a great number of parameters and choices made by the analyst. In such contexts, mistakes will occasionally happen; either systematic errors, random errors or simply unreasonable choices made in the study design and throughout the process. Such mistakes will inevitably happen when a data-intensive method like LCA is carried out manually. Such errors were found in some of the collected studies and were corrected for in the bLCAd-tool. Random errors from variations in parameters as well as unreasonable choices made in the study design are also detectable with the tool. Outliers can be identified by comparing the results with representative materials, quantities, and buildings in the database, where anomalies can be further investigated.

The current database design is customized for the context of the collected studies but is built for flexibility. The categorical data can easily be customized to different needs, while the general database structure is likely to evolve. Although the collected studies are performed according to the Norwegian context, there is no limitation on the integration of studies from other geographical regions, as all that is needed is a sufficient data resolution to enable a breakdown into building elements and life cycle phases. The tool is especially well suited to handle large quantities of assessments. The database scales seamlessly, and as the size of the database increases, its utility increases with it. The flexibility of the query structure makes the access to the data a big advantage. Data can be assembled and pivoted across building attributes, building elements, inventory, and materials to access the information relevant to a specific purpose.

In this study, the dataset was limited to 11 buildings that span many buildings types. It follows that the analysis should not be taken as representative of buildings in general; rather, it expresses the results found in the collected studies and the variations between them. The results in the applications presented here are indications based on this sample, and results are likely to change considerably as the sample size increases.

The deployment and systematical use of such a database must ultimately happen through adoption by practitioners. This can take place as standards and buildings regulations adopt reporting schemes for embodied emission results. These reporting schemes should require high resolution on results such as presented in this paper, in a digital, universally compatible format. To facilitate this deployment, the data entering process of the database must in future work be streamlined and simplified, taking into consideration the time-constraints of practitioners. This roadmap will enforce a standardization of embodied emissions results for buildings.

5. Conclusions

Embodied emission assessments of buildings suffer from a lack of consistency. This paper presented a database tool for handling large quantities of embodied emission assessments of buildings in a systematic way to improve consistency and comparability and demonstrated some useful applications based on a preliminary dataset. A model for standardizing the reporting and characterization of embodied emissions in the built environment was presented. The adoption of this method by practitioners would help produce systematic data, leading to comparable results and reliable embodied emission statistics. With a growing dataset to base the analyses on, the tool shows potential to be valuable for addressing the knowledge gap of how to reduce the carbon footprint of buildings and neighborhoods and to establish benchmarks by which this reduction can be measured.

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Appendix A

The ERD of the database is shown in Figure A1, showing the structure of the data storage.

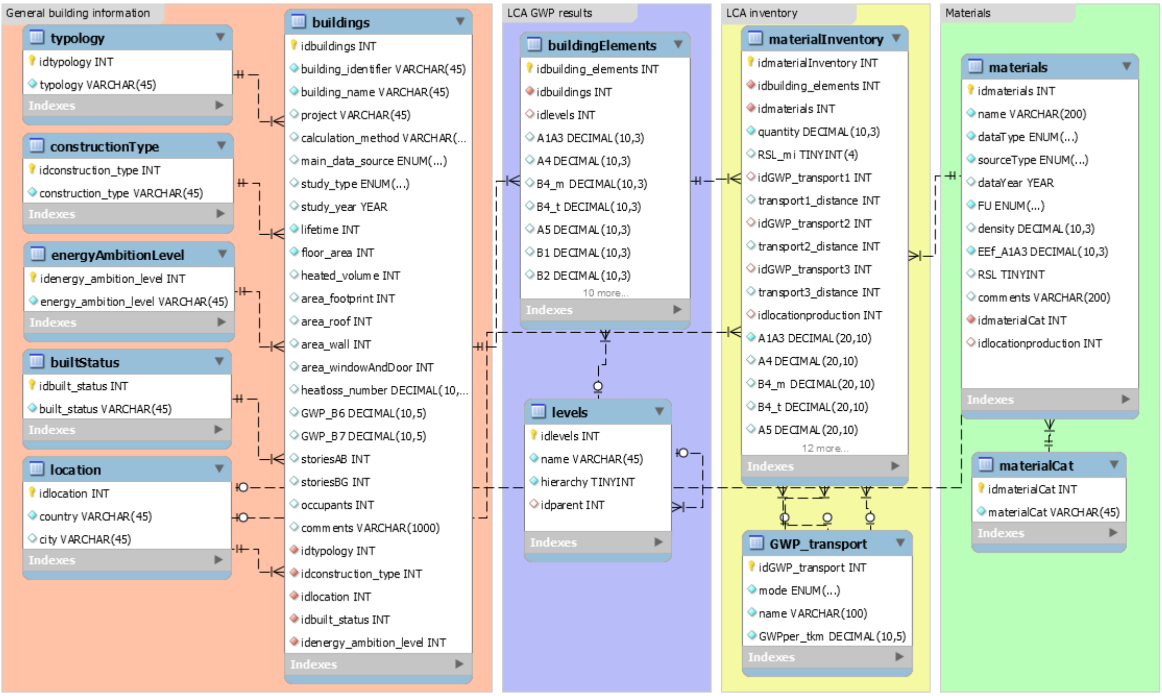

Figure A1. The Entity-Relationship Diagram (ERD) of the database used for storing the data.

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Paper II

An analytical method for evaluating and visualizing embodied carbon emissions of buildings

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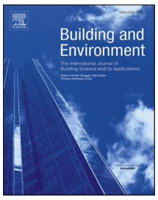

An analytical method for evaluating and visualizing embodied carbon emissions of buildings

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ABSTRACT

Greenhouse gas emissions associated with buildings constitute a large part of global emissions, where building materials and associated processes make up a significant fraction. These emissions are complicated to evaluate with current methodologies due to, amongst others, the lack of a link between the material inventory data and the aggregated results.

This paper presents a method for evaluating and visualizing embodied emission (EE) data of building material production and transport, including replacements, from building life cycle assessments (LCAs). The method introduces a set of metrics that simultaneously serve as a breakdown of the EE results and as an aggregation of the building's inventory data. Furthermore, future emission reductions due to technological improvements are modeled and captured in technological factors for material production and material transport. The material inventory is divided into building subparts for high-resolution analysis of the EE. The metrics and technological factors are calculated separately for each subpart, which can then be evaluated in relation to the rest of the building and be compared to results from other buildings. Two methods for evaluating and visualizing the results are presented to illustrate the method's usefulness in the design process.

A case study is used to demonstrate the methods. Key driving factors of EE are identified together with effective mitigation strategies. The inclusion of technological improvements shows a significant reduction in EE (11.5%), reducing the importance of replacements. Furthermore, the method lays the foundation for further applications throughout the project phases by combining case-specific data with statistical data.

1. Introduction

Buildings account for 32% of the total global final energy use, 19% of energy-related greenhouse gas (GHG) emissions and approximately one-third of black carbon emissions [1] and thus represent one of the critical pieces of a low-carbon future. In order to reduce energy use in buildings through country-level regulation, the Energy Performance of Buildings Directive [2] and the Energy Efficiency Directive [3] has been established by the European Commission. This has motivated research, new building codes, and the development of concepts that provide guidance for high energy efficiency and low carbon emissions from buildings.

Life-cycle assessment (LCA) is a standardized method [4] frequently used to give an overview of how various types of environmental impacts accumulate over the different lifecycle phases and elements of a system. It provides a basis for identifying environmental bottlenecks of specific technologies and for comparing a set of alternative scenarios with respect to environmental impacts [5,6]. LCAs have been increasingly used to evaluate the environmental performance of buildings [7] and is the method of choice for quantifying building-related GHG emissions from raw material extraction, building material production, transportation, operation, and decommissioning over the building lifetime.

Embodied emissions (EE) embedded in the production and maintenance of buildings become increasingly important in construction projects where energy efficiency is prioritized [8–11]. For the eight analyzed Norwegian cases in Ref. [12], embodied impacts were found to be 60–75% of total emissions, confirming the importance of embodied impacts in Norwegian low-carbon buildings. For the Swiss national building stock, the contribution of construction material to total life cycle emissions of residential buildings has been estimated to increase from 19% in 2015 to 39% in 2050 [13] due to reduced building energy

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consumption. Since low operational energy demand is already a regulatory priority in most countries, a stronger focus should be set on EE from materials [14]. While country-level regulation has led to strict building codes on operational energy performance, the EE is yet to be regulated. Pilot initiatives exist for the inclusion of EE in Norwegian building codes [15], but relevant unsolved problems include a lack of representative reference EE values and low transparency and comparability of the assessment methodology [16,17].

EE and embodied energy are closely related. Although there is large variation between studies, in a recent literature review transportation energy is found to be on average 6%, construction energy 10%, and demolition energy 3% of the energy embodied in building materials. The recurrent embodied energy due to replacements and maintenance is approximately 25% of total lifecycle embodied energy (excluding demolition energy) in a building with 50-year service life [8]. In a comprehensive building stock model from 2018 [13], Swiss 2015 residential GHG emissions from material use are found to be caused mostly by the input of concrete (31%), insulation material (23%), minerals (18%), brick (12%), and wood (6%), and material end-of-life is dominated by the disposal of insulation material (4%) and wood (1%).

The most influential material-related parameters for environmental performance have been identified as material choice, building lifetime, and material service life [11,18,19]. In addition, better design, increased reuse of materials, and stronger policy will help the transition to a low-carbon built environment [20 24]. The EE from future replacements can be expected to decrease with time due to technological improvements in material technology, production technology, recycling rate, prefabrication, automation, transportation technology, and the electrification of those processes together with decarbonization of the energy grid. The influence of material service life is affected by future technological improvements, and previous research [25] has pointed out the importance of including such improvements in future work.

LCA methodology for quantifying the EE requires large amounts of case-specific data from each lifecycle phase investigated. Due to the difficulty of interpreting this data and the numerous mathematical operations that go into LCA calculations, it is customary to only interpret the resulting EE at building or building element level, leaving out important information on the background for the results. This lack of a link between the background inventory data and the results reduces the usefulness of the LCA by leaving out information relevant for interpretation. Thus, there is a need for an improved methodology to provide simplified analytical relations describing the system mathematically with links to the background inventory data.

The number of LCA studies on buildings is large [26], and opens up huge potential to make use of data from previous studies. In a previous paper by the authors, a database tool for systematically organizing and storing previously conducted building LCAs at full resolution was presented [16]. The building LCA database tool (bLCAd-tool) stores the data used in the original LCA calculations in an SQL database tailored for EE analysis of buildings. This method makes all data easily accessible and available for analysis and further use in a range of applications. This data can be used to produce statistical reference values that can be used as a proxy in early-phase LCA calculations, to supplement missing data throughout the project phases, and to create benchmarks by which a case study can be compared. However, to make such statistics useful and representative, there is a need for a method that categorizes the building inventory into subparts of the building and then extracts useful metrics for each subpart.

This study presents an efficient, structured and parametrized assessment of EE in LCAs of buildings, that gives a better understanding of driving factors of the building s GHG emissions related to material production, transport, and replacements. In this paper, we present a method for linking the background inventory data of an LCA with the EE results through the following metrics: (1) the total quantity of the subpart, (2) the emission factors of the subpart, (3) the replacement factors of the subpart over the study period (material lifetime factor), (4) the transport distance of the subpart from the factories to the building site, (5) the transport emission intensity, and (6) the replacement emission factors of the subpart over the study period. The metrics simultaneously serve as a breakdown of the EE results and as an aggregation of the background inventory data. The EE of future replacements of materials is implemented in this method by adjusting future emissions for each subpart by a technology factor for production and another for transport. These factors take into account the year of replacement for each material and the time-development of the emission factors.

The utilization of the method is dependent on procedures for systematically evaluating and visualizing the results, and the paper presents two methods of visualization that can be used as tools to evaluate the EE of a case-building or a statistical building type. As proof of concept, the method and its visual applications are exemplified with case-specific values from a case building. The applications based on statistical values will be further elaborated on and applied on a statistical set of case buildings in a future paper.

The analytical framework, the methods for evaluation and visualization, and the case study building are presented in section 2, the applications for design improvements are demonstrated with a case study in section 3, and the method and model are discussed in section 4.

2. Methods

This section first presents a novel methodology for working with EE data from building LCAs in 2.1 2.4. Tools for visualizing results from the methodology are introduced in 2.5 and the case building is presented in 2.6. The method in the case study is implemented as an add-on feature of the bLCAd-tool [16] but is here formalized to be universally applicable.

The European standard EN 15978 [27] describes a calculation method for LCA of buildings. In it, the lifecycle phases are divided into modules A-D. In this paper, the system boundary is set on modules A1-A3 (production of building materials, cradle-to-gate), A4 (transportation of building materials to the building site), and B4 (replacements of building materials throughout the building lifetime/study period). In this paper, B4 is further divided into material production, B4m, and material transport, B4t, analogous to the two initial lifecycle modules (see Table 1). This division allows for performing calculations on and evaluating production and transportation separately also for replacements.

The method is outlined in a flowchart in Fig. 1. The building specific data (green) is used together with additional model definitions (blue) to calculate the model results (grey).

Building specific data. The building specific data includes building and study information (building lifetime/study period and heated floor area (HFA)), and the lifecycle inventory (LCI). For the lifecycle phases related to material production (A1-A3, B4m), the inventory data needed for each material or component are the (1) quantity, (2) emission intensity, and (3) lifetime. For the transport of materials (A4, B4t), the additional data needed are the (4) traveled distances and the (5) specific emissions of the transport modes.

Model definitions. The model definitions include (1) defining building subparts as subsets of the inventory and (2) defining technology development vectors.

Model results. The results are calculated for all subparts. The EE results per m^2 are capturing the final effect of all choices on the resulting EE, including design choices, construction technologies, and material choices. The metrics Q, F, L_F, D, T, and L_{DT} (see Table 2) are a breakdown

Table 1
Material use lifecycle phases according to the adjusted European standard EN 15978 [27].

	Initial material use	Replacements
Material production, cradle-to-gate	A1-A3	B4m
Transport from factory to building site	A4	B4t

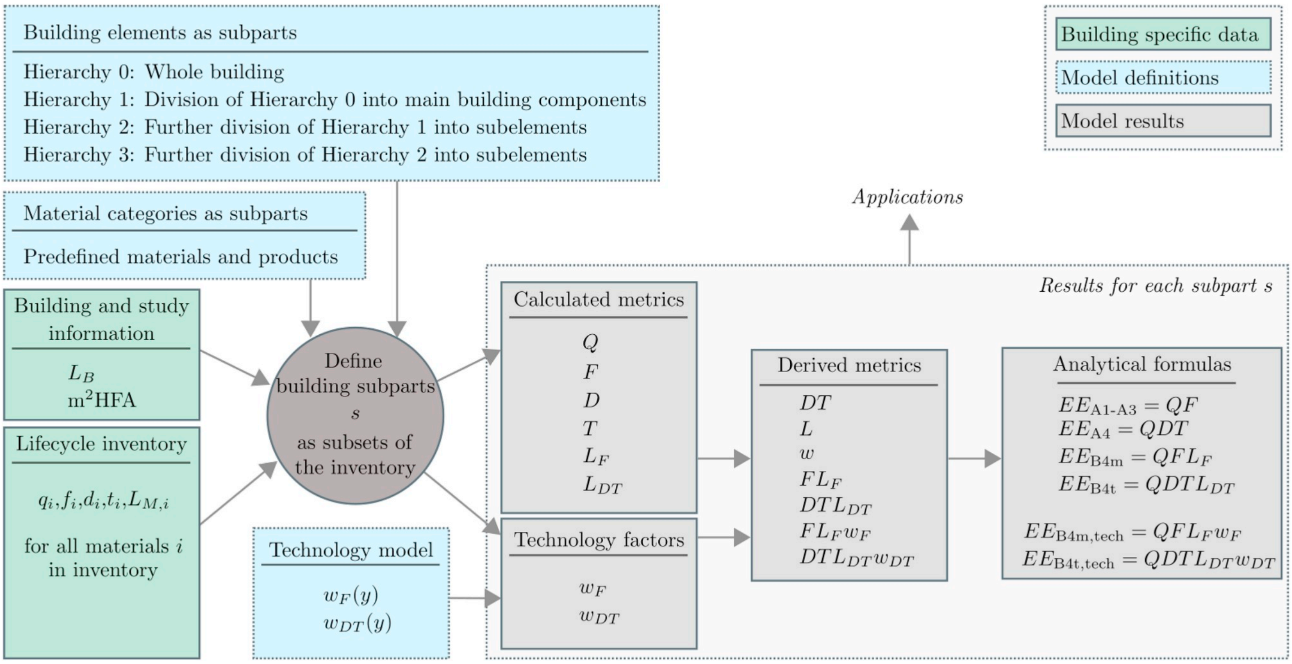

Fig. 1. Flowchart of the method.

of the EE and are thus isolating the contribution from individual factors. The technological factors w_F and w_{DT} are additional measures of the effect of future technological developments. Combinations of these metrics lead to a set of derived metrics. The metrics are related to EE by analytical formulas. Analyzing the metrics for a building and its subparts clarify what the potential of alternatives for reduced EE are.

Table 2
The metrics and technological factors, their units, and interpretation.

	Factor	Unit	Interpretation
EE	EE	kgCO$_2$e./m^2	Embodied emissions; the final effect of all choices, indicates where the focus should be when aiming for reduced impact
Metrics	Q	kg/m^2	Quantity; the total mass of building materials per heated floor area
	F	kgCO$_2$e./kg	Production emission factor; emission intensity of material production
	DT	kgCO$_2$e./kg	Transport emission factor; emission intensity of material transport. Product of distance, D, in km and emission intensity of transportation, T, per kg and km
	L_F	Multiplier, fraction	Production lifetime factor; the fraction of material production EE added due to material replacements throughout the building's lifetime
	L_{DT}	Multiplier, fraction	Transport lifetime factor; fraction of material transportation EE added due to material replacements throughout the building's lifetime
	L	Multiplier, fraction	Total lifetime factor; the fraction of total emissions added due to replacements
Technology factors	w_F	Multiplier, fraction	Production technology factor; the change in future emissions from material production due to technological improvements
	w_{DT}	Multiplier, fraction	Transport technology factor; the change in future emissions from material transport due to technological improvements
	w	Multiplier, fraction	Total technology factor; the total change in future EE due to technological improvements

2.1. Defining the metrics

The building specific data (see Fig. 1) is linked with the EE results through the metrics in Table 2. The metrics simultaneously serve as a breakdown of the EE results and as an aggregation of the building specific data. The metrics are calculated for building *subparts*. The subparts are in this study defined as building elements (BE), according to the Norwegian standard NS 3451 Table of Building Elements [28], and additionally, as material categories (MC), according to a set of predefined material and product groups. Yet, the subparts can be any arbitrary subset of the material inventory. For example, building subparts can be the whole building, individual BE, individual MC, MC within a BE, BE within an MC, etc. The metrics are calculated based on the data used in the original LCA calculation, and summarize amongst others the quantity, emission factors, and replacement emission factors of subparts.

The quantity Q of the subpart is the sum of the quantities q_i of each material i that goes into the subpart

$$Q \quad \sum_i q_i \tag{1}$$

The specific emissions from material production F of the subpart is the quantity-weighted average of the specific emissions f_i of all materials i in the subpart

$$F \quad \frac{\sum_i q_i f_i}{\sum_i q_i} \tag{2}$$

The production lifetime factor L_F is the quantity- and specific emission-weighted average of the lifetime factors

$$L_F \quad \frac{\sum_i q_i f_i l_i}{\sum_i q_i f_i} \tag{3}$$

where l_i is the lifetime factor of the material, $l_i \quad L_B \;\; L_{\text{M}\,i} \quad 1$; L_B being the lifetime of the building (study period) and $L_{\text{M}\,i}$ the service lifetime of the material. The transport distance D of the subpart is the quantity-weighted average distance from the factory to the building site of the materials i in the subpart

$$D \quad \frac{\sum_i q_i d_i}{\sum_i q_i} \tag{4}$$

where d_i is the distance for material i. The transport emissions per kg and km, T, is the quantity- and distance-weighted average transport emission factor of each material i in the subpart

$$T \quad \frac{\sum_i q_i d_i t_i}{\sum_i q_i d_i} \tag{5}$$

where t_i is the transport emissions per kg and km of material i. If the material is transported by several transport modes with differing transport emission factors, then an additional distance-weighted averaging of the transport emission factors t_i must be performed. The transport lifetime factor L_{DT} is the quantity-, distance-, and transport emission-weighted average replacement factor of the materials in the subpart

$$L_{DT} \quad \frac{\sum_i q_i d_i t_i l_i}{\sum_i q_i d_i t_i} \tag{6}$$

Similarly, as for T, if there are several transport modes with differing emission factors, an additional distance weighted averaging of the transport emission factors t_i is necessary. Multiplying D with T gives a specific emission factor for the transport analogous to what F is for material production. DT and F have the same units, which is useful because they can then be compared directly. In the calculations, however, it is beneficial to keep D and T separate since this retains the original information of the material inventory data, and thus can be evaluated independently.

2.2. The metrics analytical relations to embodied emissions

The LCA calculation methodology can be reformulated into simplified formulas consisting of the metrics. These metrics can then be used to gain insights into the driving factors of the LCA results. The metrics' relations to the initial EE and future EE with and without technological factors are shown in Table 3. In the following, the EE calculation of a building or a building subpart based on the quantities and weighted average parameters of subparts is formalized. The equations give the same results as a standard attributional LCA calculation.

The EE from the production of initial building materials (A1-A3) in subpart s are

$$EE_{\mathrm{A1}\quad\mathrm{A3}\,s} \quad f\; Q_s \;\; F_s \qquad Q_s F_s \tag{7}$$

and the EE from production of replacements (B4m) are

$$EE_{\mathrm{B4m}\,s} \quad f\; Q_s \;\; F_s \;\; L_{F\,s} \qquad Q_s F_s L_{F\,s} \qquad EE_{\mathrm{A1}\quad\mathrm{A3}\,s} L_{F_s} \tag{8}$$

The EE from the transport of initial building materials (A4) are

$$EE_{\mathrm{A4}\,s} \quad f\; Q_s \;\; D_s \;\; T_s \qquad Q_s D_s T_s \tag{9}$$

and the EE from the transport of replacements (B4t) are

$$EE_{\mathrm{B4t}\,s} \quad f\; Q_s \;\; D_s \;\; T_s \;\; L_{DT\,s} \qquad Q_s D_s T_s L_{DT\,s} \qquad EE_{\mathrm{A4}\,s} L_{DT\,s} \tag{10}$$

Combining these equations, we get the total emissions for the subpart for these four lifecycle phases

$$\begin{aligned} EE_s \quad & EE_{\mathrm{A1}\quad\mathrm{A3}\,s} \quad EE_{\mathrm{A4}\,s} \quad EE_{\mathrm{B4m}\,s} \quad EE_{\mathrm{B4t}\,s} \\ & Q_s F_s \quad Q_s F_s L_{F\,s} \quad Q_s D_s T_s \quad Q_s D_s T_s L_{DT\,s} \\ & \quad Q_s \;\; F_s \;\; 1 \quad L_{F\,s} \quad\; D_s T_s \;\; 1 \quad L_{DT\,s} \end{aligned} \tag{11}$$

Counterintuitively, the fractions of emissions added due to replacements, L_F and L_{DT}, are not the same, since the metrics are weighted by the parameters of each material. The lifetime factors L_F and L_{DT} can alternatively be combined into a single lifetime factor L by an emission-factor weighted averaging which gives the following alternative formula for the total emissions

$$EE_s \quad Q_s \;\; F_s \quad D_s T_s \quad 1 \quad L_s \tag{12}$$

where $L \quad \frac{FL_F \;\; DTL_{DT}}{F \;\; DT}$. This metric is, for instance, useful for determining the total additional EE added throughout the lifetime.

2.3. Technological factors

The emissions related to the production of materials as well as emissions from their transport can be expected to decrease in the future due to technological improvements in material technology, production technology, recycling rate, transportation technology, and the electrification of those processes together with the decarbonization of the energy grid. The technological factors presented in Table 2 are introduced to take these future emission reductions into account. Both technological factors are calculated based on vectors of assumed developments in emission reductions of material production emission factor F, $w_F \;\; y$, and in transport emission factor DT, $w_{DT} \;\; y$, for each year y in the study period. This time-dependent emission reduction in the expected year(s) of replacement for each material is then used in the calculation of an average weighted by the initial EE, and thus giving more importance to materials with high initial EE. This results in two factors that adjust the future emissions by the expected emission reductions in the year(s) of replacement for each material inventory in the subpart

$$w_F \quad \frac{\sum_i q_i f_i w_F \;\; y_i}{\sum_i q_i f_i} \tag{13}$$

$$w_{DT} \quad \frac{\sum_i q_i d_i t_i w_{DT} \;\; y_i}{\sum_i q_i d_i t_i} \tag{14}$$

where $w_F \;\; y_i$ and $w_{DT} \;\; y_i$ are the fractional emission reductions in the year of replacement y_i, from material production and transport of material i, respectively. For materials that are replaced more than once, the reductions $w_F \quad {}_1 \; y$ and $w_{DT} \quad {}_1 \; y$ are the average $w_F \;\; y$ and $w_{DT} \;\; y$ from all replacement years. To take into account future reductions in emissions of material production and transportation, the EE equation above is expanded to include the additional technological factors for adjusting B4m and B4t. The equation for calculating the EE of the material production and transportation including technology estimation for future replacements then becomes

$$EE_s \quad Q_s \;\; F_s \;\; 1 \quad L_{F\,s} w_{F\,s} \quad\; D_s T_s \;\; 1 \quad L_{DT\,s} w_{DT\,s} \tag{15}$$

The technology factors w_F and w_{DT} can alternatively be combined into a single technology factor w by a replacement emission-factor weighted average which gives the following alternative formula for the total emissions

Table 3
The emission factors and how they relate to EE with and without future developments in technology taken into account. The initial and future EE refer to the lifecycle phases of Table 1.

	Emission factors	Lifetime factors	Tech factors	Replacement emission factors wo/tech impr.	Replacement emission factors w/tech impr.	Initial EE	Future EE wo/ tech impr.	Future EE w/tech impr.
Production	F	L_F	w_F	$F{\cdot}L_F$	$F{\cdot}LF{\cdot}w_F$	$Q{\cdot}F$	$Q{\cdot}F{\cdot}L_F$	$Q{\cdot}F{\cdot}L_F{\cdot}w_F$
Transport	DT	L_{DT}	w_{DT}	$DT{\cdot}L_{DT}$	$DT{\cdot}L_{DT}{\cdot}w_{DT}$	$Q{\cdot}DT$	$Q{\cdot}DT{\cdot}L_{DT}$	$Q{\cdot}DT{\cdot}L_{DT}{\cdot}w_{DT}$

(16)

where $w \quad \frac{FL_F w_F \quad DTL_{DT} w_{DT}}{FL_F \quad DTL_{DT}}$. This metric is, for instance, useful for determining the total reduction of replacement EE due to the technological factors.

2.4. Interpretation

The metrics and equations have physical interpretations that can be used for evaluation of the EE of a building subpart. The methodology treats any chosen subpart of the building as a unified product that has its own metrics. This means that for any subpart of the building, or the whole building, the EE can be broken down into these components and an interpretation of what is causing the emissions is available for identifying potential improvements.

The metrics can give insights into how well choices are made in the design and planning of the building, in terms of their impact on EE. The design of the building, the quantities of materials needed per functional unit, the emission intensity of the production of the materials and products chosen, their transport distance and transport emission intensity, as well as their durability and the need for replacements, can all be interpreted for individual building subparts and for the building as a whole. The metrics thus provide information on how well the building and its subparts are planned in terms of EE.

The technological factors are calculated based on a projection of the change in future emission intensities compared to those of the initial year and can be interpreted as how much technological improvements will affect replacement EE, taking into account the year of replacement and which materials are replaced and at what rate.

To make the EE results comparable to other buildings, one can apply a normalization. In this paper, the normalization used is the heated floor area (HFA). This is done by dividing the metric Q by the HFA of the building. The remaining metrics are already directly comparable since they do not depend on the quantities.

2.5. Methods for evaluating and visualizing results

Visualizing the results is important for making them practical and comprehensible for the analyst. The two visualization and evaluation methods described here can be equally used for statistical metric values and case-specific metric values.

The Metrics chart is visualizing the EE and the breakdown into metrics for a set of defined subparts of the building. Fig. 2 shows an example of a Metrics chart. In the first column, the EE of each lifecycle phase is presented in a stacked bar where each lifecycle phase is color-coded by the metric associated with it. All lifecycle phases, and thus the total EE, are linearly dependent on quantity Q of the second column. The initial emissions, A1-A3 and A4, are in addition linearly dependent on the emission factors F, DT of the third column. By multiplying the emission factors F, DT by lifetime factors L_F, L_{DT}, and by the technology factors w_F, w_{DT}, we get the technology adjusted replacement emission factors $FL_F w_F$ and $DTL_{DT} w_{DT}$ in the fourth column. The replacement emissions, B4m and B4t, are linearly dependent on the replacement emission factors. For case-specific data, the chart will show the calculated metrics for that building. For statistical data, the metrics chart can, for instance, show the average values, in addition to their distributions as error bars for each BE and metric. The metrics chart can also display both types of data at once, to compare and benchmark a case building against statistical values represented by error bars.

The *Q-F-DT* Plot and the *EE-*L_F*-*L_{DT} Plot are two-dimensional representations of the metrics. Fig. 3 shows an example of each plot. Each connected line shows metrics from one subpart which is identified by a number. The resulting EE is shown along the curved contour lines. The *Q-F-DT* Plot shows the initial EE, with a breakdown of the emissions into quantity Q along the horizontal axis and emission factors F and DT along the vertical axis. The *EE-*L_F*-*L_{DT} Plot shows the replacement EE, with a breakdown of the emissions into initial EE along the horizontal axis (and is thus dependent on the *Q-F-DT* Plot) and the technology adjusted lifetime factors $L_F w_F$, $L_{DT} w_{DT}$, and Lw, along the vertical axis. Minimizing the values along both axes for both plots will reduce EE, and the focus for design improvements should be on the subparts with highest values on the contour line axes. Moreover, their horizontal and vertical values show how to theoretically reduce the EE most efficiently by the relative magnitudes of each metric along the two axes. Both case-specific data and statistical building type data can be presented in *Q-F-DT* and *EE-*L_F*-*L_{DT} plots to visualize case results or the emission profiles of building types.

2.6. The case study building

The method requires building specific data, model definitions for subparts, and a technology model, as shown in Fig. 1. The case study building is the single-family residential building ZEB Living Lab, which was built as a living laboratory by the Research Centre for Zero Emission Buildings [29] in 2014. This case was chosen because its inventory is fairly complete, and it has been well documented in the literature [11,12,25,30 32]. The one-story (no basement), 102 m^2 HFA timber building was intended to have net zero GHG emissions from the production of building materials and their transportation to the building site, including replacements of materials, and operational energy use throughout its postulated lifetime of 60 years, by compensating for its emissions by renewable onsite energy generation from PV-panels on its roof that would substitute grid electricity. An LCA of the building was performed on the final design by the research centre. The building specific data was acquired by the authors and inserted into the bLCAd-tool which stores the data used in the original LCA calculations in an SQL database tailored for EE analysis of buildings [18]. The methodology presented in this paper was then applied to that data. The

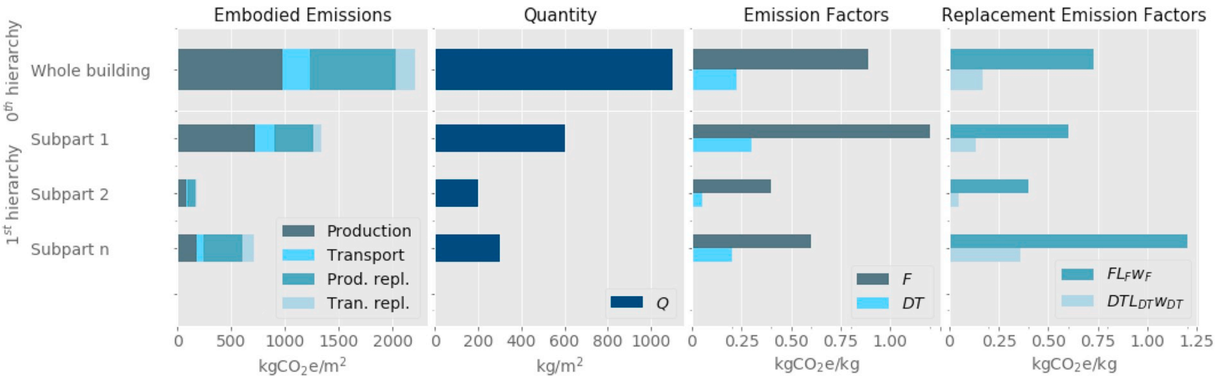

Fig. 2. Example of a Metrics chart visualization showing the EE of each lifecycle phase and a breakdown into the metrics.

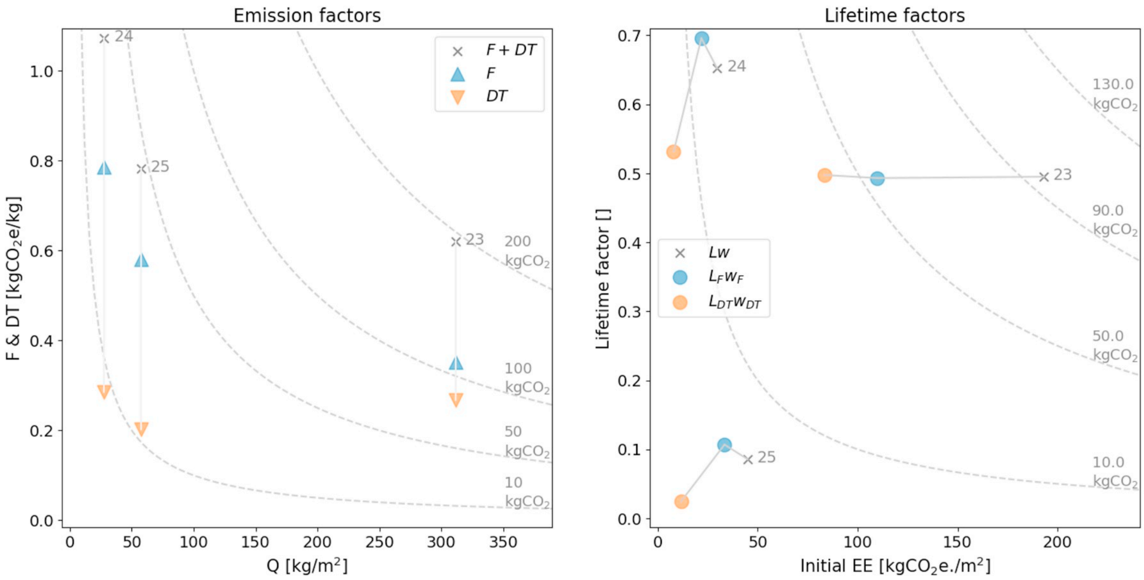

Fig. 3. Example of the *Q*-*F*- *DT* plot (left) and the *EE* - L_F - L_{DT} plot (right). The numbers next to the connected lines refer to subparts of the building.

original study included dishwasher, fridge and freezer, washing machine, tumble drier, hob, and oven; these are in this study not considered as parts of the building and are not included. All remaining inventory items except one, aluminum sealing tape, are included in the calculations. This item was excluded due to missing density value and accounts for 0.1% of the EE. In a comparative study of similar low-carbon buildings, the case building had the highest EE/m^2 [12].

The subparts are defined as BE and as MC. The BE subparts are divided into four hierarchies of BE (see Fig. 1) according to the standard NS 3451 [28] with all the BE that was included in the original assessment of the building. The 0th hierarchy includes all materials included in the inventory of the study, while the 1st, 2nd, and 3rd hierarchies have an increasing resolution on the specificity of the BE. A higher hierarchy includes all materials from lower hierarchies, with the exception of the 3rd hierarchy which only includes the BEs that are specified at this resolution; in this case study, those are sub-elements of 23 Outer walls and 26 Outer roof. The MC subparts are categorized by a list of predefined materials and products, where each material inventory item of the original assessment gets assigned to a category. This means that although some products consist of more than one material, such as the hot water tank, they are organized as separate MCs. Conversely, other products are included in the inventory as several materials. Windows and doors, for example, are in the case study divided across aluminium, steel, timber, plastics, rubber, paint, glass, and so on.

The technology factors w_F for production and w_{DT} for transport are included in the calculations of replacement EE and is here modeled as a linear interpolation between today s emission factor (100% of initial values both for production and transport) and the assumed reduction in the final year of the study (50% of initial value for production and 10% for transport in year 2074).

3. Case study results

This section applies the method to the case study to demonstrate its use in the design and evaluation phases of a building construction project. Two applications for evaluation through visualization are presented: the Metrics chart, and the *Q*-*F*- *DT* and *EE* - L_F - L_{DT} plots. The same visualizations can also be used for statistical data from building types which may be useful in other project phases. The results in this section are a demonstration of the methodology and the visualization tools applied to case-specific data. Numerical results are provided in a spreadsheet in the supplementary materials.

3.1. *Metrics chart*

The Metrics chart for the case building is shown for BE in Fig. 4 and for MC in Fig. 5.

The first row in Fig. 4 shows the overall EE for the Whole building and the distribution among the lifecycle phases, the total quantity per HFA, and the building s overall performance of emission factors and replacement emission factors. The lower hierarchies show how these EE and metrics are distributed among the BE.

On the 1st hierarchy, the majority of EE fall into Envelope, foundations, and structure . This is regardless of the observation that it has the lowest emission factors and the lowest replacement emission factors, and is due to practically all material quantity going into this BE. On the contrary, more than a quarter of EE come from Electric power , not due to large quantities, but due to very high material production emission factor (*F*) and replacement emission factor ($FL_F w_F$). Heating, ventilation, and sanitation has low quantity and also lower emission factors and replacement emission factors and therefore low EE. The emissions from the BE on the 1st hierarchy can be further investigated by looking at their sub-elements on the 2nd hierarchy.

On the 2nd hierarchy, among the sub-elements of Envelope, foundations, and structure (beginning with the digit 2), the Outer walls and Outer roof stand out as having the highest emissions followed by 'Stairs and balconies . These are thus the most important BE to focus on in the main building construction. Outer walls has a large quantity, which can be expected given that outer walls make up a large area of the building envelope. The emission factor for Outer walls is small relative to the other BE, however, a further reduction in the emission factor will have a great impact on overall emissions due to the large quantities. 'Outer roof has large quantities, but also high production emission factor. Reducing any of those, or reducing them in combination, will impact the building s EE significantly. Stairs and balconies has surprisingly large quantities for a one-story building, and the production emission factor is also of significance. This BE could therefore also be an area of focus for design improvements. Among the sub-elements of 'Electric power (beginning with the digit 4), Other tech: Photovoltaic is responsible for nearly all the EE, due to having the highest production emission factor and production replacement emission factor of all materials in the entire building. This BE includes technical components and mounting board in addition to the PV panels. Of particular note is that the replacement emission factor is higher than the emission factor, even after technological improvements. This is due to a short lifetime of 15

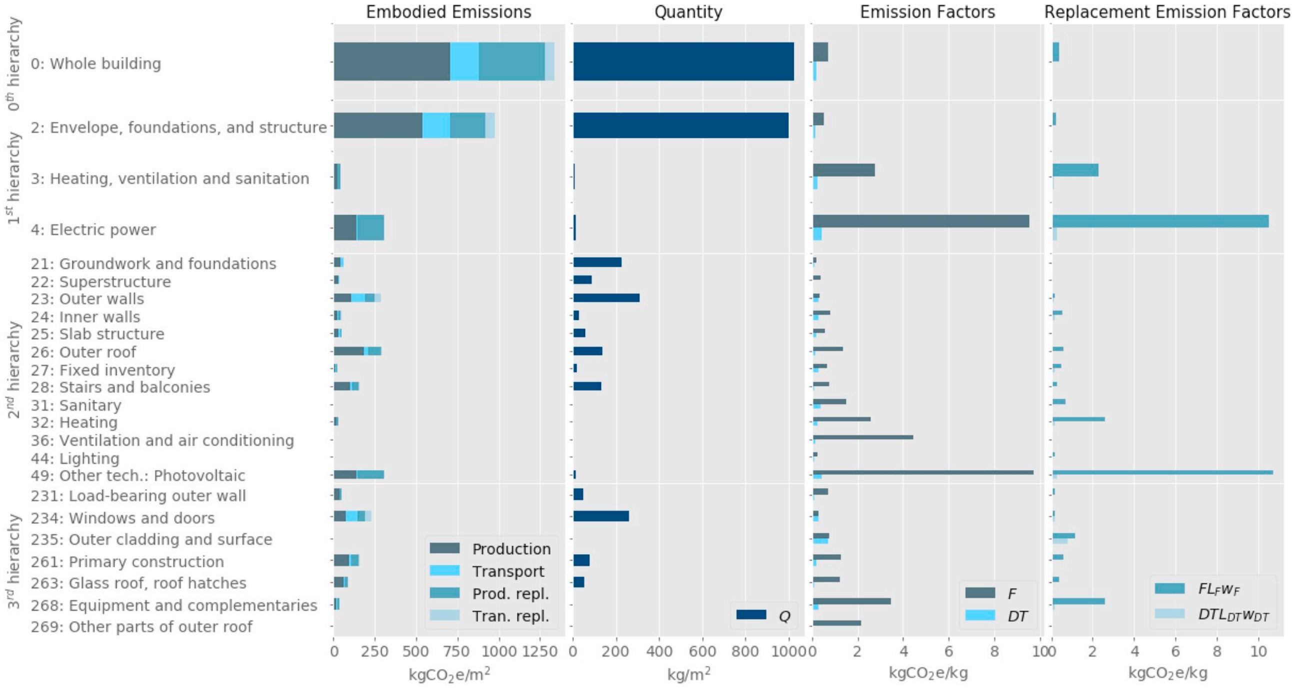

Fig. 4. Metrics chart for the case building with subparts defined as BE. The columns show from left to right (1) the EE of lifecycle phases A1-A3 material production, A4 material transport, B4m replacement-material production, and B4t replacement-material transport; (2) quantity of materials per heated floor area Q; (3) emission factor for material production F and for material transport DT; (4) replacement emission factors $FL_F w_F$ and $DTL_{DT} w_{DT}$.

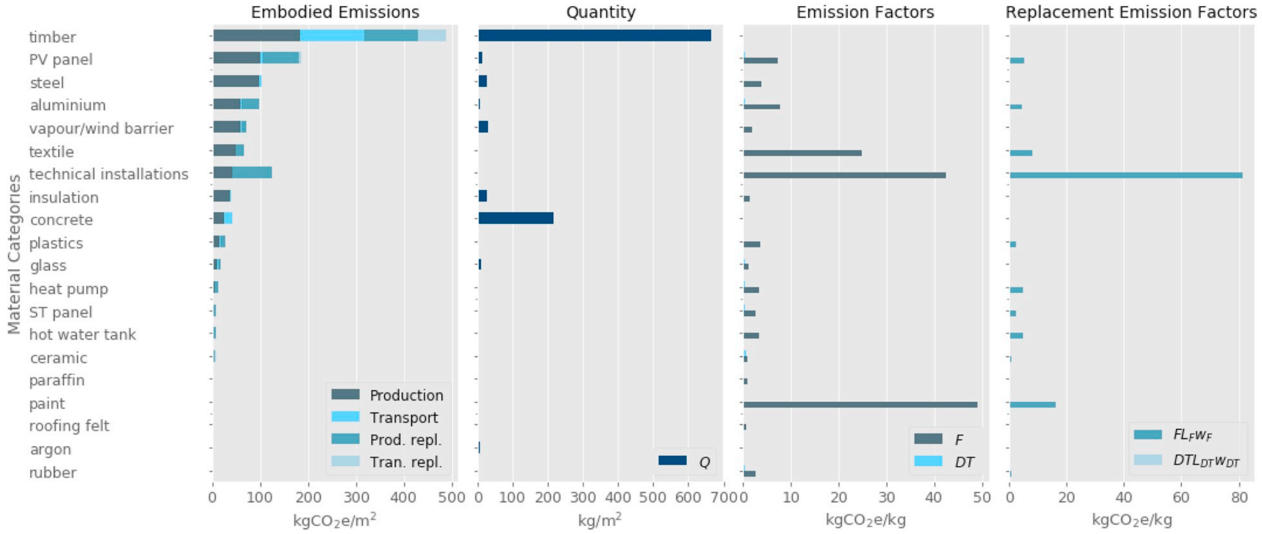

Fig. 5. Metrics chart of the case building with subparts defined as the whole inventory separated into MC. The columns show from left to right (1) the EE of lifecycle phases A1-A3 material production, A4 material transport, B4m replacement-material production, and B4t replacement-material transport; (2) quantity of materials per heated floor area; (3) emission factor for material production F and for material transport DT; (4) replacement emission factors $FL_F w_F$ and $DTL_{DT} w_{DT}$.

years for the inverter component, which has high EE. Among the subelements of Heating, ventilation, and sanitation , none are of particular importance.

’Outer walls and Outer roof are further separated into their subelements on the 3rd hierarchy (beginning with digits 23 and 26, respectively). For Outer walls , Windows and doors dominates emissions mostly due to the large quantity. For Outer roof , the Primary construction is dominating, followed by Glass roof, roof hatches . These both have significant quantities, emission factors, and replacement emission factors.

The effect of building design on EE can be indirectly interpreted from the same figure. The 2nd hierarchy shows Outer walls to be responsible for the largest quantity, and the 3rd hierarchy further shows that ’Windows and doors is the main reason for the high quantity. Since the quantity is given per m^2 HFA, the building design is indirectly contained in this metric and is an indication of large areas of windows and doors relative to the HFA. The information obtained from analyzing the Metrics chart should, however, be used in conjunction with architectural drawings and will together inform the analyst on where the greatest potentials for EE reductions lie.

Fig. 5 shows the Metrics chart for the case building s MC. It shows that the top categories are responsible for most of the EE, while the bottom categories are insignificant and can be ignored.

Among the categories that do matter, there are two main trends. The first includes timber and concrete , which together make up most of the building mass. It is mainly due to their large quantities, and not their emission factors, that EE is high. The building is a timber building, and the quantity of wood is thus high. Concrete is used only in the foundation, and because of its high density, its EE is high despite its low emission factor. The other trend applies to the remaining categories, which, relative to timber and concrete, have smaller quantities but high emission factors. Notably, technical installations has high emission factor and also high replacement emission factor due to a short material lifetime (high L_F). The exact balance between quantity, emissions factors, and replacement emission factors varies and determines the possibilities for emission reductions.

3.2. *Q-F- DT and EE - L_F- L_{DT} plots*

The culprits among the metrics in terms of their contribution to the EE can be further explored by two-dimensional plots that show the contribution of each metric and the resulting emissions. In the Metrics chart in Section 3.1, it was established that 2 Envelope, foundations, and structure is responsible for most of the EE. In the following, the focus is on that BE only. The *Q-F- DT* and *EE* - L_F - L_{DT} plots for this BE on hierarchies 1, 2, and 3 are shown in Fig. 6.

On the 1st hierarchy, the first column shows the emission factor for production F and for transport DT together with their total emission factor along the contour lines for the resulting EE. The quantity is the same for all three, and reducing the quantity will reduce emissions proportionally. However, by following the contour lines one can see that reducing the quantity will have a larger effect on EE from F than from DT. The EE from production dominates, and a fractional reduction in F will have a larger effect than a reduction in transport emission factor DT. The second column shows the emissions from replacements, where the technology adjusted lifetime factors determine how much EE is added to the initial EE during the lifetime of the building (shown on the contour lines). The largest fraction added is for future production of materials, and a smaller fraction is added for transport.

On the 2nd hierarchy, the value of the methodology applied to design improvements becomes apparent. Here, the BE 26 Outer roof and 23 Outer walls stand out as the most important contributions to initial EE, followed by 28 Stairs and balconies . Although the two former have about the same amount of EE, 26 Outer roof EE is mainly caused by a high emission factor F, while 23 Outer walls EE is mainly caused by a large quantity. However, a reduction of EE for both is achieved along the gradients of the contour lines, emphasizing the importance of keeping the focus on reduction along both axes. The theoretically most efficient way of reducing EE is therefore along the gradients of the contour plot. For 26 Outer roof , this gradient is directed mostly towards lower quantities, while the gradient for 23 Outer walls is directed mostly toward lower emission factors. The EE from replacements are dominated by the same BE as for the initial emissions, but not because they have the highest lifetime factors, rather as a consequence of the initial EE being high. The gradients, and therefore the optimal reductions, are in the directions of a reduction of both initial EE (quantities of materials used in the design and their emission factors) and the lifetime factors (reducing the need for replacements).

The 3rd hierarchy is only showing the BE specified at this hierarchy, which for this building is sub-elements of 23 Outer walls and 26 Outer roof . Here, 234 Windows and doors (of the outer walls) and 261 Primary construction (of the outer roof) dominate EE. Following the same logic as above, the EE from 234 Windows and doors will have the largest reduction by reducing the emission factors, while 261 Primary construction would benefit the most from a combined reduction of both quantity and production emission factor. The replacement EE of these BE can be reduced by reducing the need for replacements, as well as reduced quantities and emission factors in the initial EE.

3.3. *Importance of the technological factors*

Including the technological factors w_F and w_{DT} for the replacement EE leads to a more realistic estimation of the EE than excluding the effect of future emission reductions, as is normal to see in building LCAs. Fig. 7 shows the total reductions in future EE per BE and MC. The production replacement emission factor and thus also the production replacement EE is reduced by 18.6%. Likewise, the transport replacement emission factor and thus also the transport replacement EE is reduced by 59.4%. The total reduction in replacement EE is 27.8%, leading to an overall EE reduction for all four lifecycle phases of 11.5%. The replacement EE is 71.2% of initial EE without technological factors and significantly less at 51.4% when included.

4. Discussion of method and model

4.1. *Added value*

A number of shortcomings in current methodologies for reduction of EE in the planning of buildings were discussed in the introduction. The methodology presented in this paper addresses several of those by breaking down EE of material production, transport, and replacements into subparts (BE and MC) and a further breakdown into the metrics. This hierarchical structure allows for EE analysis across many levels of detail; from the aggregated to the specific. Furthermore, the breakdown into metrics allows for evaluating the importance of different driving factors for each subpart. The effect of future technological emission reductions in material production and transport is quantified by technological factors. This effect is significant and including it increases the validity of the results. Two visualization tools are introduced to evaluate the EE of a case building. These visualizations imply the theoretically optimal way of reducing emissions. In practice, it may prove difficult to achieve these metric reductions. However, this information can guide the analyst in the direction of optimal improvements, and in combination with architectural drawings and BIM models serve as a valuable tool for design improvements. The methodology does not only highlight which subparts of the building to focus the reductions, but more importantly, how to best address the emission reduction. The results from the case study clarify (1) which subparts that are of importance and (2) to what extent the quantity, choice of material, and transport of materials are driving factors for the EE of the subpart. Once a subpart has been singled out, the metrics provide information on how to approach the emission reduction.

From equations (11) and (15) it can be read that EE is linearly dependent on the material quantity Q, i.e. reducing the quantity will reduce the EE of the subpart proportionally, and will do so for all four lifecycle phases. Reducing the specific emissions from material production, F, will reduce the first term in the bracket proportionally, while a reduction in the specific emissions from material transportation, DT, will reduce the second term proportionally. A reduction in the lifetime factors, L_F and L_{DT}, (or in $L_F w_F$ and $L_{DT} w_{DT}$ if the technological factors are included) will not reduce the EE linearly but will depend on their initial value. An initial value close to or larger than 1 will mean a relatively larger reduction, while a small value compared to 1 will have little impact on EE. Based on the above, and previous studies showing the production term to be larger than the transportation term [8,11], the metrics can be ordered by their potential for reduction in EE when there is a proportional reduction of each metric: Q, F, DT, L_F, L_{DT}. This ordering is generally true for the building level and for many subparts, however, the ordering will depend on the initial values of the metrics.

In this study, the presented method is applied to buildings. Buildings are complex products and therefore a good area of application. The method would, however, be the same for any product. Furthermore, this study applies the method only to the impact category Global Warming Potential (GWP). The methodology would, however, be the same for any impact category.

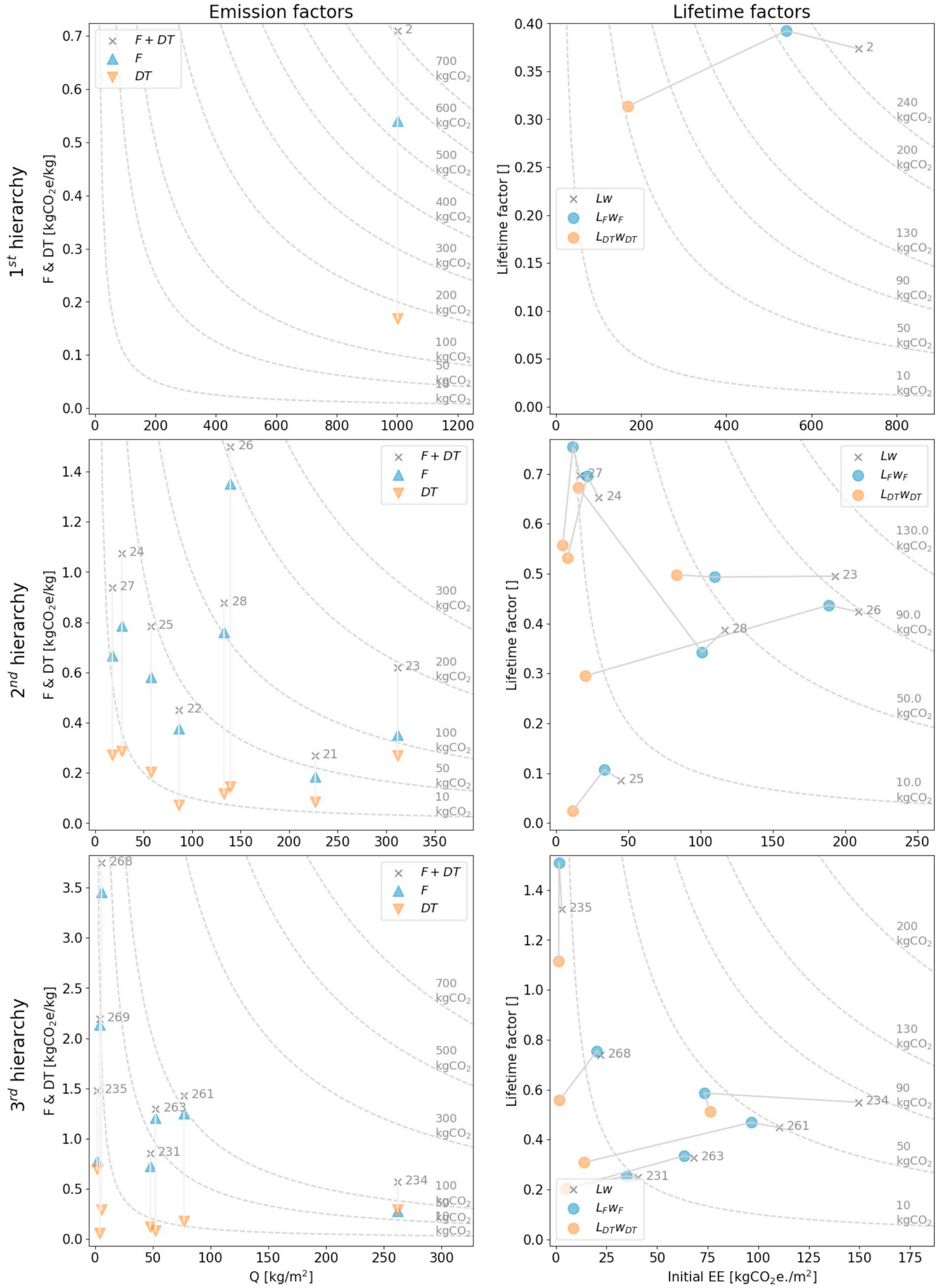

Fig. 6. The *Q-F- DT* plots in the left column show the EE in kgCO$_2$e./m^2 of the initial lifecycle phases broken down by quantities and emission factors. The *EE* - L_F - L_{DT} plots in the right column show the EE of the replacement lifecycle phases broken down by initial EE and lifetime factors. The dashed contour lines are the products of the horizontal and vertical axes and show the resulting EE. The plots show results from building element 2 Envelope, foundations, and structure from the case building at the 1st, 2nd, and 3rd hierarchies, where BE are numbered according to NS3451. Building element names for the numbering can be found in Fig. 4.

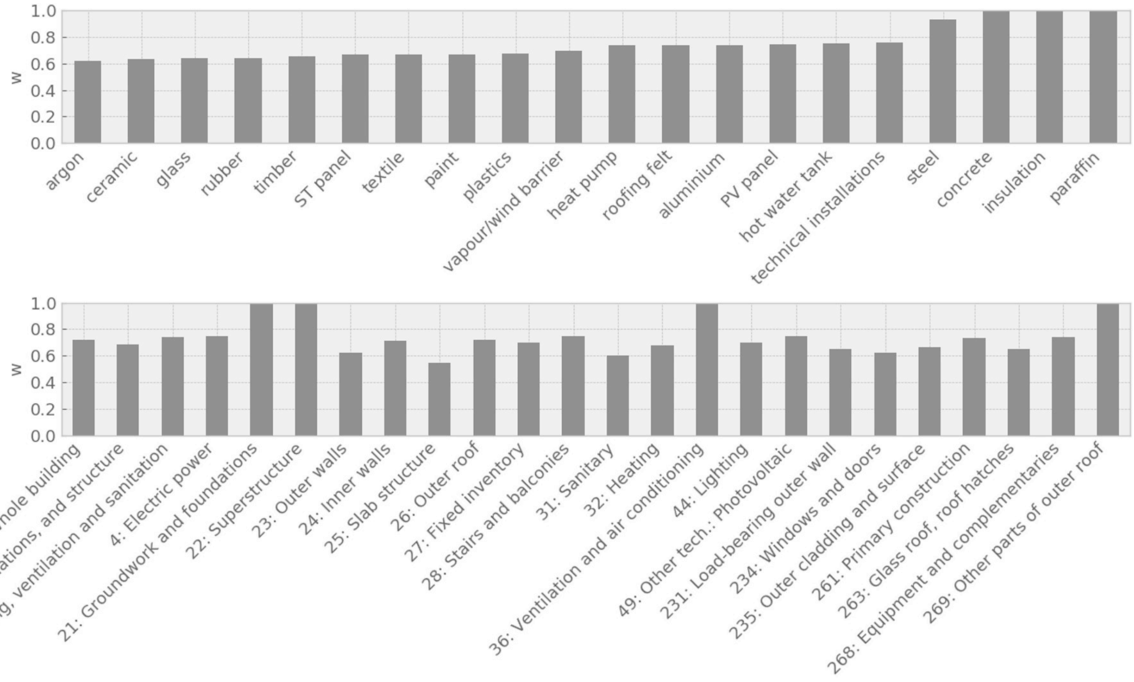

Fig. 7. Total technology factor *w*. The reductions in future EE from replacements due to technological improvements, shown for MC (top) and for BE (bottom). A value of 1 signifies that the subpart is not replaced during the study period.

4.2. *The relevance of future emissions*

Material service life and building lifetime are two of the three most influential parameters for environmental performance [18,19]. When designing a building for low material-related EE, the material service life is often brought forward as one of the most important parameters to prioritize. However, one must not ignore the importance of expected future developments in production and transport technologies, and their ongoing decarbonization. While [33] found low-carbon energy production strategies to reduce the total carbon emissions of planned residential Finish area by 10% only, the potential of the decarbonization of the energy mix, which will influence the carbon intensity of the final products is not to be underestimated. The carbon intensity of final products depends on the carbon intensity of all upstream processes in the global and local production chains, and decarbonizing emission hotspots , typically by replacing coal electricity by low carbon electricity in global production chains will reduce the carbon intensity of the final products significantly [33 35].

Including the technological factors in the calculations significantly reduces the importance of the future replacement lifecycle-phases, and thus emphasizes the importance of keeping the main priority on near-future emissions. Building LCAs should therefore always discount future EE. Not only does this downgrade the importance of the building material lifetime, it also reduces the importance of the much-debated lifetime of the building itself, which is often a rather arbitrarily set study period. This study period is often part of the functional unit, where resulting emissions are divided over the lifetime. This greatly increases the uncertainty and may lead to misleading results. In this study, the building-lifetime parameter is only used for the number of replacements needed. This ensures that initial emissions are far more accurate. With a discounting of future emissions, the importance of the building lifetime is reduced also for future emissions, with decreasing marginal emissions for extra years added.

4.3. *Validation of method and model*

The results from the method are dependent on the quality of the LCI of the case study, which may have corrupted or uncertain values, and may lack materials in the inventory. The method and model, however, reproduced the previously published case study results. Additional validation was performed on six more case buildings, which also reproduced the results. Thus, the model has been validated, and any systematic or random error must therefore be attributed to the LCI of the original case study.

4.4. *Limitations*

Our model has a number of limitations. The following aspects should be given attention when applying the model and when evaluating results.

The method includes the lifecycle phases of production, transport, and replacement of construction materials, which is not a holistic picture of the EE in a building s lifecycle. Most notably, the construction and end-of-life phases are not considered. Material waste was not part of this study, but is an important emission source in both of these phases, as well as in the replacements phase [36]. Operational energy use is not part of the EE, but is an important emission source and should be included in a holistic assessment.

Emission reductions from technological improvements in production and transport are uncertain and are here modeled in a simplified way. The technological development vectors (used to calculate technological factors) are in the case study modeled as a linear decrease from the year of construction until the end of the study period, and are the same for all materials. However, the method is independent of this linear development and can be replaced by any development model, for instance, exponential decay. Not only can technological developments be based on more accurate models in future work, but different scenarios can also be explored. Moreover, the technological development vectors are assumed to be the same for all building materials. In reality, the future emissions of each type of material is dependent on its current emission level and its unique production and transport conditions. This implementation is thus a simplification of reality. The same approach can be performed separately for each material or MC to increase accuracy. Doing this will, unfortunately, complicate both the practicality of the method and its interpretability. It may thus not always be desired, especially considering the inherent uncertainty of future developments. The method leads to independent factors for each subpart that are applied post-assessment. This modular way that the technological factors are implemented in the method, namely by a single development vector for production and one for transport, enables high flexibility for updating and creating different scenarios.

The quantities (mass) of materials do not contain information about their structural qualities, and therefore do not alone describe the benefits of choosing those materials. A material may, for instance, have high structural strength per weight but be widely used in a building and therefore still have high quantities.

A major limitation of the method at its current state is its lack of quantifying the accuracy of the judgments and their probable magnitudes. Results must be sufficiently valid if they are to be used for judgments about how to construct buildings, and quantified uncertainties are necessary for validating results. This can be implemented in the method by calculating error propagation and confidence intervals; it is thus an expansion of the method that is necessary and can be tackled by further developments. The current method does, however, improve the transparency of which BE and lifecycle phases that are included in the system boundary. Moreover, the calculated metrics for each subpart gives insight into the LCI data, which can be evaluated to see if the data is reasonable. The approach presented in this paper, therefore, improves the transparency of the system boundaries as well as of the inventory data and lays the groundwork for verifying each metric against statistics.

4.5. Further work

Uncertainties of case study results should be quantified and can be visualized as error bars. In a future paper, we look at the uncertainty and also look into the optimal improvement strategies for emission reductions by investigating the sensitivity and correlations of the metrics.

By collecting previous building LCAs and producing statistics for the metrics of subparts, further applications can be developed. To be representative for a case study, statistics can be produced based on datasets that are separated into different building types. By use of the analytical formulas, the statistical metrics can be used to calculate EE for subparts of similar buildings. Applications include gaining statistical insights from emission profiles of building types; early-phase EE estimation; increasing the completeness of the assessment by use of proxy values in place of missing values and for subparts outside of the system boundary; two main types of evaluation of environmental performance: evaluation of ‘isolated study performance , i.e. analyzing the data of the case study only, and benchmarking the study against statistical reference values; verifying the study design and data against statistical values. These applications together form a workflow throughout the project phases from earliest phase to final operation that reduces uncertainty, increases completeness, and improves the capabilities of EE assessments.

Statistical EE values of building types on a detailed subpart level, and a further split into metrics, will result in representative reference values that enable future building codes to regulate the EE of building materials. Such values can be representative for case-specific conditions that affect EE and have increased transparency and comparability compared to building level EE results. Our efforts should be coordinated with other research groups, by taking part of community driven material intensity research platforms such as proposed by Ref. [37].

This paper applies the method on the building scale, but with a growing focus on neighborhood planning [38], the method can be applied also on bigger scales by introducing an additional hierarchy before the building level. This hierarchy can include the buildings in the neighborhood as well as materials used for transportation and for infrastructure. In such cases, data collection becomes an even bigger issue, and the utility of statistical proxy reference-values therefore increases further.

5. Conclusions

In this paper, we presented a procedure for systematically evaluating and visualizing the EE results of LCAs of buildings material production, transport, and replacements. This was done by grouping a building s inventory into building subparts and calculating metrics for each. These metrics simultaneously break down the EE into individual driving factors and summarize a data-rich inventory for enhanced interpretation. The method is suited to aid practitioners when designing buildings and in the final evaluation phase. The information obtained from analyzing the metrics can be used in conjunction with architectural drawings and will inform the analyst on where the greatest potentials for EE reductions lie.

This approach has advantages compared to previous classical LCA in that it offers a more structured and efficient assessment of EE. A better understanding of driving factors is provided by parametrization of the EE, which improves interpretation. In addition, future expected emission reductions are taken into account by technology factors for production and transport. Taking future emission reductions into account significantly reduces the importance of the lifetime of the building materials and the replacement EE.

The method will be expanded to include uncertainty in a future paper. Additionally, the method lays the foundation for a multitude of further applications in that it allows for mixing case-specific data with statistical data. This is useful when case-specific data is unavailable, such as in the early project phases, and in later project phases for estimation of building subparts that are outside the system boundary of an assessment. Applications of the method with statistical data can be developed to provide a basis for EE assessment throughout the project phases of construction projects. The current method can be directly applied to case buildings for identifying design and material choice improvements, and for evaluation after construction is completed. In the future, the combination of case-specific and statistical metric values can be useful if EE should be included in building code regulations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106476.

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Paper III

Embodied emission profiles of building types: guidance for emission reduction in the early phases of construction projects

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Preliminary statistical results based on papers I and II.

Embodied emission profiles of building types: guidance for emission reduction in the early phases of construction projects

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Abstract. The embodied emissions of the construction materials in buildings are a significant contributor to climate change but have only rarely been systematically studied by statistical methods. In the early phases of a building project, empirical results of statistical emission profiles of different building types can act as useful guiding information to inform decisions regarding reduced embodied emissions from construction materials. However, engineers and architects do not have such information at disposition. In this paper, the embodied emissions from the production and transport of initial and recurring building material use in 7 Norwegian case studies of low-emission buildings are made comparable and then studied statistically to find out how the impact varies with building types. The building types studied are timber residential, concrete office, concrete school, and concrete swimming hall. Statistics are produced for each building type and are broken down by the impact contribution from different building elements and material categories. This results in embodied emission profiles and material use profiles for these four building types, which, when based on a larger dataset, can be used by architects and engineers to make informed decisions when aiming for reduced embodied emissions in the early phases of a construction project. Additionally, these profiles can be used as benchmarks by which the final building can be compared when the building is constructed. The statistical results are preliminary and based on a limited dataset, which makes them applicable only as an indication for Norwegian low-emission buildings of these four building types. Future work includes expansion of the dataset on which the profiling is based, further development of the statistical method, and applying the methodology to additional building types.

1. Introduction

The construction and operation of buildings is a major source of global greenhouse gas emissions, and with increased energy efficiency due to stricter building codes and a focus on energy renovations, the emissions associated with the building materials are making up an increasing portion [1, 2, 3]. These indirect emissions are often denoted 'embodied emissions', as opposed to the operational emissions from energy and water use. The European standard EN 15978 [4] which is describing a calculation method for life cycle assessment (LCA) of buildings divides the emissions into lifecycle phases. The lifecycle phases for material production from cradle-to-gate are named A1-A3, the transport from the factory to the building site is A4, and B4 is the replacement of building materials. B4 can be further divided into production and transport as is done for the initial lifecycle phases, and can then be denoted B4m and B4t as was done in [5].

Operational energy efficiency is now a regulatory priority in most countries, and a stronger focus must be set on emissions from materials [6]. While national building codes enforce regulations on operational energy performance, there is no equivalent regulation for the embodied emissions. Some initial work for the inclusion in Norwegian building codes is ongoing [7], however, unsolved problems include lacking representative referential values and low transparency and comparability of the assessment methodology [8].

A construction project goes through several project phases from initial ideation, to the solidification of a plan, construction, and final operation. The information available about the building will increase along with these phases, but will vary from project to project. In the earliest project phases, statistical emission profiles of different building types can be used to get an idea of the variation between – and the range within – subparts of certain types of buildings that are being considered. Building types can be compared against each other to see the effect of choices made in the earliest project phases. The lack of information in early project phases, when little has been decided about the area plan and building composition, makes it difficult if not impossible to make informed decisions at this stage. Statistical results from building types can then serve as guidance. Building types are likely to have trends in the EE results giving each building type a unique emission profile. Statistical insights on the emission profiles and material use of building types can be derived from a sufficient dataset of representative buildings.

In addition to aid in improving the design of the building relative to itself, it would be useful to benchmark environmental performance against other building projects within the same building type. In the design phases, feedback on how the building and its subparts compare to other buildings of the same building type can point the analyst in possible directions for improving the design. In the evaluation phase, benchmarking can serve as documentation for building code requirements and certification schemes.

Many factors are affecting the embodied emissions of buildings, from climate to construction technologies, material production technologies, electricity generation and fuels used, transport distances and many more. When comparing the embodied emissions from one building to those of others, buildings should be categorized by these conditions. The term 'building types' is used here as a set of common characteristics that the buildings share, and that have an impact on the EE, such as location, typology (i.e. school, kindergarten, office building, etc.), and construction type (i.e. timber, concrete, steel, etc.). A building type can be general and include most buildings, i.e. have few restrictions on the descriptors, or can be specific and include only very similar buildings, i.e. have strict restrictions on the descriptors. By using data from similar building types, the generated statistics and thus the comparison is made representative for the case. Furthermore, each building consists of an inventory of building materials. Buildings can be broken down into subsets of their inventories, here referred to as subparts. This breakdown into subparts of building types makes comparisons more representative, by reducing the variability from both building characteristics and from building inventories [5, 8].

This paper presents a method for obtaining statistical emission profiles for greenhouse gas emissions related to the production, transport, and replacement of building materials for four different building types. The applications of the method include gaining statistical insights from emission profiles of building types and for benchmarking environmental performance against statistical reference values.

2. Methods

The statistics are based on 7 previously conducted LCAs of buildings, presented in Table 1, that were collected from various sources. All buildings have been designed to have low lifecycle emissions both from operational energy use and emissions embodied in building materials. Due to a limited dataset, the results will be strongly biased by the case-specific conditions and designs of these buildings.

Table 1. The building LCAs that are included in this study.

Name	Typology	Construction	Location	HFA [m^2]	Year, study
ZEB Living lab	Residential	Timber	Trondheim, Norway	102	2014
ZEB Multikomfort	Residential	Timber	Larvik, Norway	202	2014
ZEB SFH Concept	Residential	Timber	n/a, Norway	160	2013
Papirbredden II	Office	Concrete	Drammen, Norway	8536	2012
Østensjø skole	School	Concrete	Oslo, Norway	3629	2017
Flesberg skole	School	Concrete	Flesberg, Norway	6664	2018
Flesberg svømmehall	Swimming hall	Concrete	Flesberg, Norway	2344	2018

The results were made comparable by systematically organizing the original data used in the studies according to the method described by Resch and Andresen in [8]. Here, material inventory of the buildings and other relevant information is stored in a SQL database that categorizes the inventory according to hierarchical building elements from the Norwegian standard NS 3451 Table of Building Elements [9], and according to material categories by predefined material and product groups.

The inventory data is then used to calculate aggregated metrics for each building by the method described by Resch et al. in [5]. Metrics that are relevant for the interpretation of the results, and furthermore, that are useful for generating statistical emission profiles, are calculated. These metrics are weighted average values of the inventory items, that describe the environmental performance of each building subpart, which in this way is treated as an isolated product. The metrics are the quantity Q [kg], the emission factors for production F [$kgCO_2e$] and for transport $\boldsymbol{D}$ [$kgCO_2e$], as well as the lifetime factors for production L_F [-] and for transport $L_{\boldsymbol{D}}$ [-], and the technological factors for production w_F [-] and transport $w_{\boldsymbol{D}}$ [-] that are adjusting the replacement emissions according to an expected decrease in future emissions. The calculation of metrics for each building element and material category is enabling a detailed interpretation of emissions. The effect of technological improvements on future replacement emissions is implemented with technological vectors modeled as linear decreases from the year of construction until the final year of the study. Production emissions are assumed to be 50% lower and transport emissions to be 90% lower 60 years after the buildings are constructed. The metrics relations to embodied emissions are shown in Table 2.

Table 2. The metrics relations to embodied emissions [$kgCO_2e$]. Names of lifecycle phases shown in parentheses.

	Initial	Replacement
Production, cradle-to-gate	QF (A1-A3)	QFL_Fw_F (B4m)
Transport, factory to building site	QDT (A4)	$QDTL_{DT}w_{DT}$ (B4t)

These methods for systematically organizing and storing the results, and for calculating the metrics, together enable the use of previous LCA studies for establishing statistical reference values. First, buildings are categorized into building type categories according to their typology and main construction material. Then, each metric within each building type is averaged for each building element and each material category. All building elements, material categories, and lifecycle phases where data exist are used for the averaging, and conversely, excluded where data is not available. The number of data points used for each statistical value is therefore varying and restricted by the available data.

This results in a set of average metric values for the building types 'Timber residential', 'Concrete office', 'Concrete school', and 'Concrete swimming hall'. These average metric values are then used to calculate the embodied emissions for each building element and material category with the equations shown in Table 2. The results are then visualized in 'Metrics charts' as described in [5]. These charts display the embodied emissions for each lifecycle phase, and the breakdown of those emissions into the quantity, emission factors, and replacement emission factors. Moreover, these results are shown for each building subpart (building element or material category) to get a high-resolution overview of the emission profiles of the building types.

3. Results

Results are first presented as a comparison between the four building types, and then separately for each. The presented results include the embodied emission results from the lifecycle phases A1-A3, A4, B4m, and B4t, as well as the quantity, emission factors, and replacement emission factors. The plots show all building subparts and lifecycle phases that are available for the building types, which is varying because each building type has included different building subparts and lifecycle phases in the original studies.

3.1. Comparison between building types

The building elements that are included in the collected LCA studies vary and the building types can therefore not be compared directly on the aggregated level. The comparison is made for the building elements 21, 22, 23, 24, 25, 26, and 28, since they are available for the four building types (except for 28 for Concrete office) (see Figure 2 for building element names that correspond to these numbers). Figure 1 shows the average metrics from these building elements for the four building types, as well as the embodied emissions calculated from the average metrics.

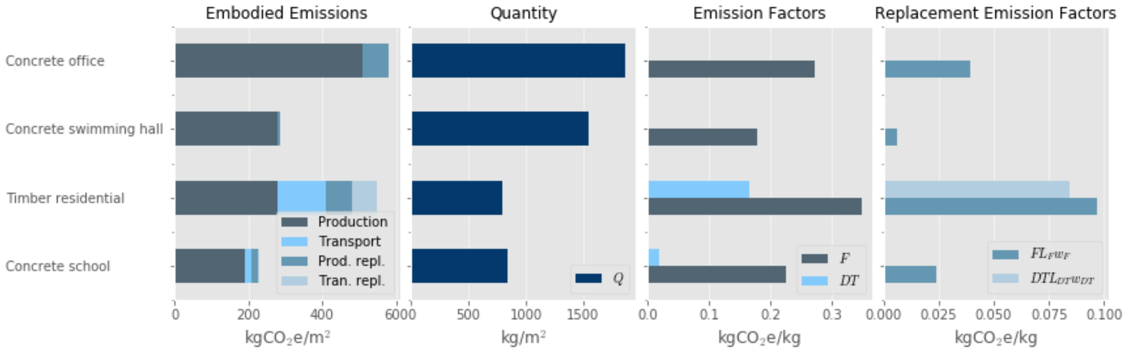

Figure 1. Comparing the emission profiles of the four building types. Building elements 21, 22, 23, 24, 25, 26, 28 are included in the comparison.

The initial production of building materials (A1-A3), available for all building types, is highest for the concrete office. This is due to a high quantity of materials per m^2 combined with a relatively high emission factor. It has 2.3 times more quantity than the timber residential, 2.2 times more than concrete school, and 1.2 times as much as concrete swimming hall. The high mass can be explained by the extensive works needed to stabilize the ground for this particular case. The emission factor for initial production, F, is smallest for swimming hall, and largest for timber residential. Their difference in emission factor is compensated for by a mass twice as large, and they end up having the same emissions from production of building materials. The smaller emission factors of the concrete buildings is partly because of concrete having high density, but is likely also affected by the residential buildings having more complete inventories. If one of the residential buildings were left out (ZEB Living Lab), then the building type based on the two remaining would have the lowest emissions of all building types and the production emission factor would be almost a third smaller. This highlights the limited usefulness small datasets.

The production of replacement materials (B4m), also available for all building types, is proportionally larger for the timber building type than for the concrete building types. Concrete is not replaced during the 60 year lifetime of the buildings, while timber is. This is reflected by the replacement emission factor $\mathbb{E}\ _F w_F$ which is 2.5-15.6 times larger for timber residential than for the concrete building types. Although timber parts are replaced more often than concrete, the timber buildings in these particular studies also have more complete inventories which contributes to the larger replacement emission factors.

The transport of building materials (A4 and B4t) have limited availability in the dataset, and thus, does not allow for a complete comparison. Nevertheless, data available on these lifecycle phases are important indications of the relevance of transport. Particularly, it is noteworthy that there is a big difference between timber residential, which has the most detailed inventory, and concrete school, with less detailed inventory.

The future replacement emissions are reduced by a technological factor corresponding to an expected development in emission reductions in production and transport, taking the years of replacement and replacement rates into account. The average reduction by building type is shown in Table 3. The reduction for the timber building type is much larger than the reductions for the concrete building types.

Table 3. The reduction of future replacement production emissions due to technological improvements.

Building type	w_F	Reduction, production	w_{DT}	Reduction, transport
Concrete school	0.970	3.0 %	0.980	2.0%
Timber residential	0.911	8.9 %	0.648	35%
Concrete office	0.969	3.1 %	-	-
Concrete swimming hall	0.978	2.2 %	-	-

3.2. Timber residential

Figure 2 and 3 show the average results from 3 timber residential buildings, where the subparts are divided into building elements and material categories, respectively. The emissions for '0: Whole building' are divided into subelements on the 1st hierarchy. The timber residential building type is the only building type where results are available for '3: Heating, ventilation, and sanitation', for '4: Electric power', and for '8: Other installations'. The system boundary is thus much more complete than for the other building types. However, '2: Envelope, foundations, and structure', which is available for all building types, is by far the most important part of the total emissions. The reason for this is apparent from the breakdown into the metrics: nearly all quantity goes into this building element. The emission factors are much higher for the other building elements, but in return, they have small quantities and therefore lower emissions. Notably, '4: Electric power' is responsible for a sizeable chunk of the overall emissions, which can be attributed further to '49: Other tech.: Photovoltaic' on the 2nd hierarchy. Looking further into '2: Envelope, foundations, and structure', the building elements on the 2nd hierarchy with digits 2x, and the building elements on the 3rd hierarchy with digits 2xx, show that '23: Outer walls', and in particular

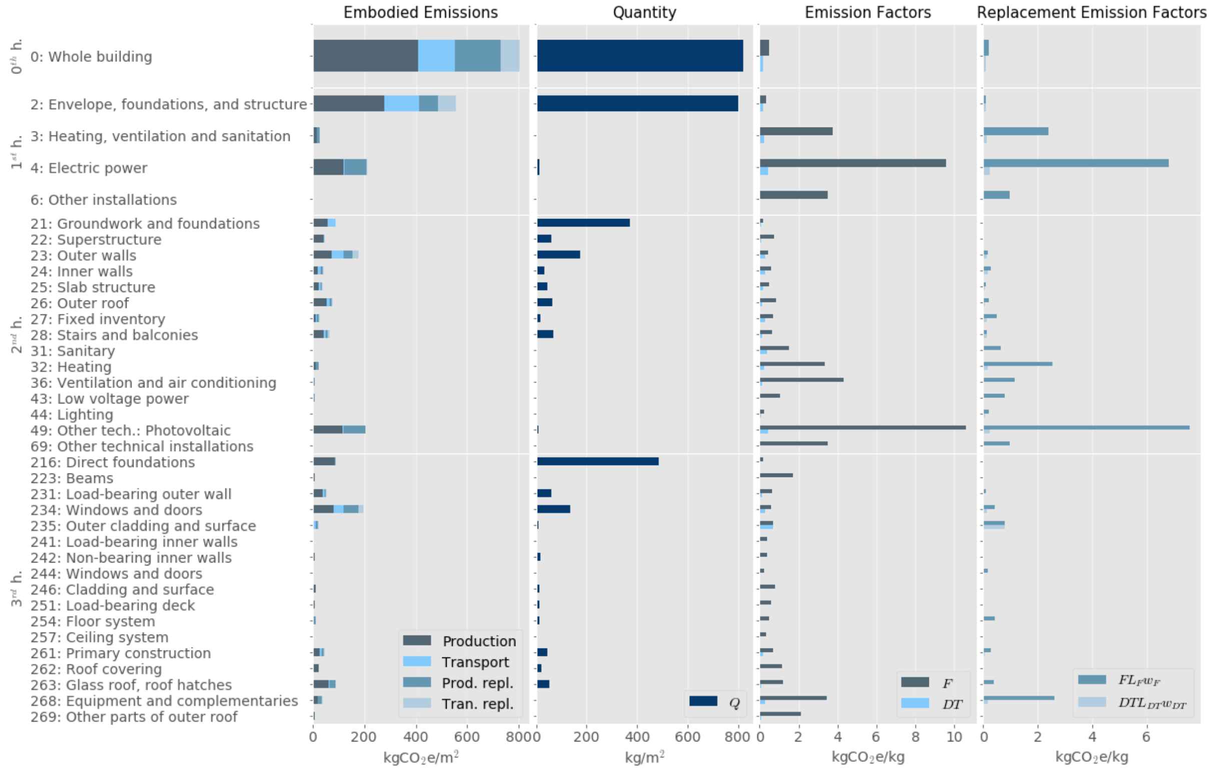

Figure 2. Timber residential (n=3).

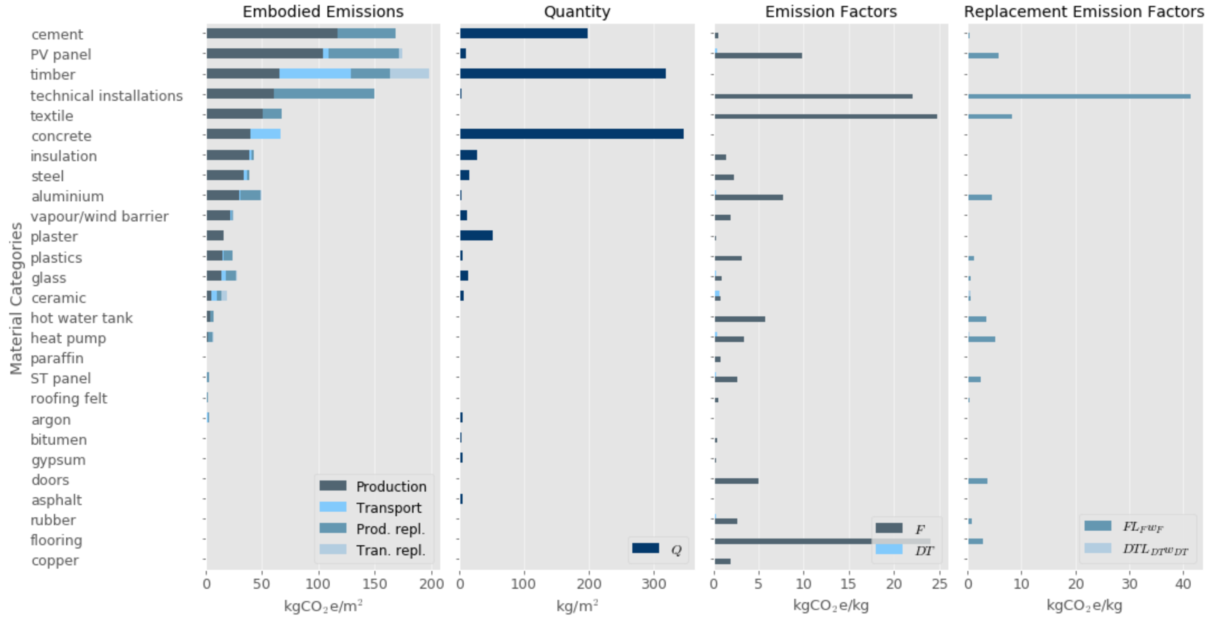

Figure 3. Timber residential (n=3).

'234: Windows and doors' are responsible for a large part of total emissions. The reason for this is a high quantity, but also significant emission factors and replacement emission factors both for production and for transportation. Further, it can be observed that '21: Groundwork and foundations' has a large quantity but small emission factors and zero replacement emission factors, while '22: Superstructure', '26: Outer roof', and '28: Stairs and balconies' all have similar emission profiles with both quantities and emission factors being relevant.

The material categories that are dominating the timber residential building type are cement and concrete (used mainly in foundation), PV panel, timber, and technical installations. Furthermore, textile, insulation, steel, aluminium, vapor/wind barrier, plaster, plastics, glass, and ceramic are also important material categories. The remaining material categories are small and should therefore not be an important focus in terms of emission reductions. Among the categories that do matter, the PV panel, technical installations, and textile have high emission factors for production and replacement production, while timber, concrete, and cement have large quantities.

3.3. Concrete office

Figure 4 and 5 show the results from 1 concrete office building, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure', and resolution restricted to the 2nd hierarchy. Transport emissions are not available. Most of the quantity is divided equally between '21: Groundwork and foundations' and '25: Slab structure', but the former has higher emission factor and therefore much higher emissions. These building elements' emissions can be attributed to large quantities of concrete and cement. '23: Outer walls' is the only building element where replacement emissions are large. Although the quantity is small, both the emission factor and replacement emission factor are the highest for the building type. In Figure 5 it can further be seen that this to a large degree is caused by the material category windows and its high emission factor and replacement emission factor.

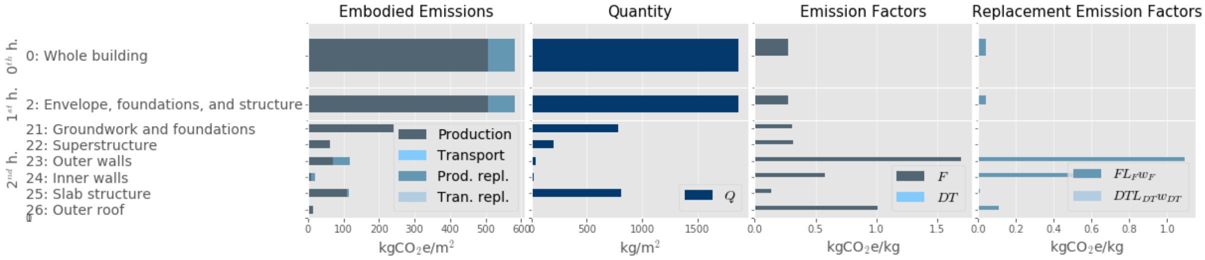

Figure 4. Concrete office ($n=1$).

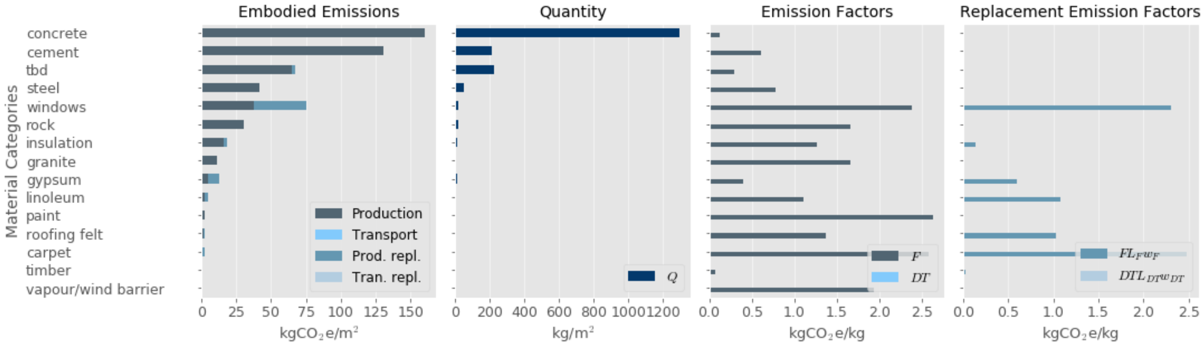

Figure 5. Concrete office ($n=1$). Uncategorized materials are grouped in *tbd*.

3.4. Concrete school

Figure 6 and 7 show the average results from 2 concrete school buildings, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure', and resolution restricted to the 2nd hierarchy. '25: Slab structure' is dominating quantity, and as a consequence it is the building element with the largest embodied emissions. '21: Groundwork and foundations' and '23: Outer walls also have substantial quantities, while '24: Inner walls' and '26: Outer roof' mainly have their high emission factors and replacement emission factors causing their contribution to emissions.

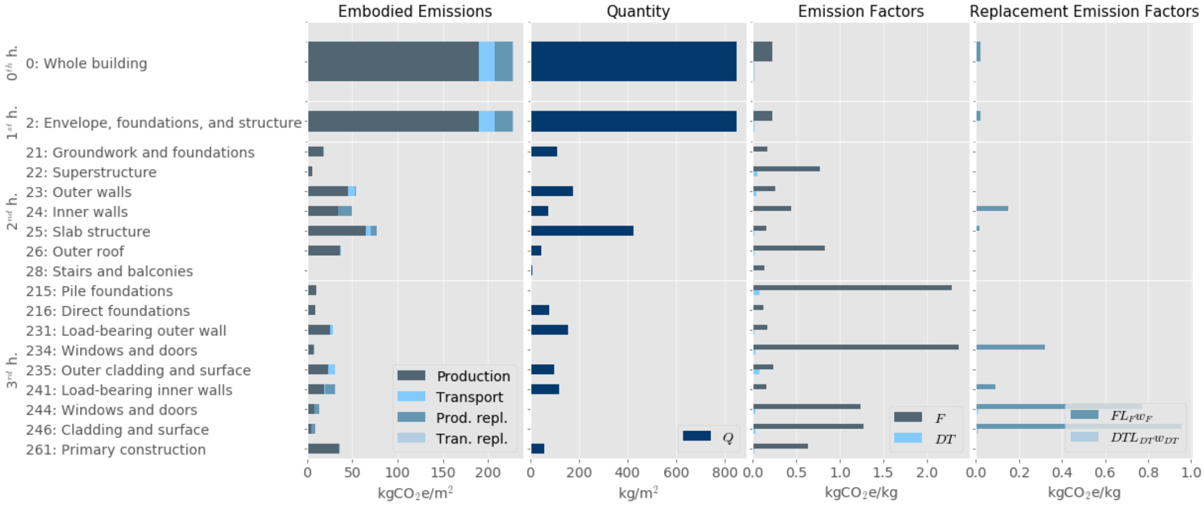

Figure 6. Concrete school ($n=2$).

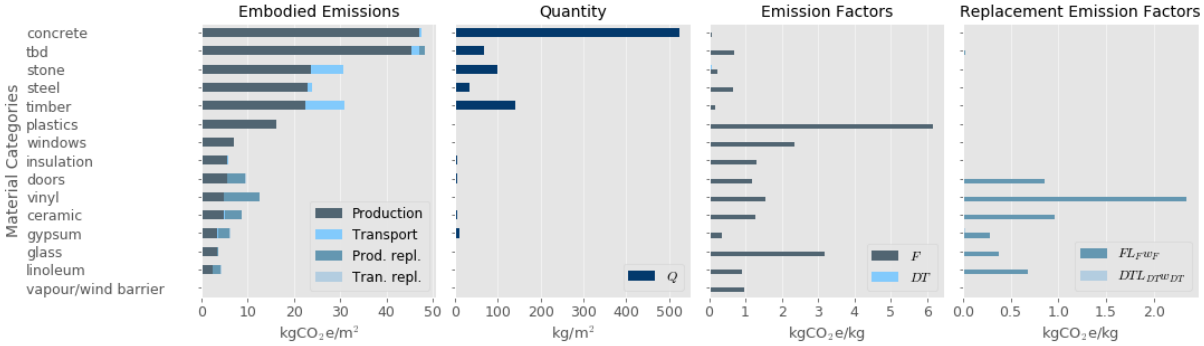

Figure 7. Concrete school ($n=2$). Uncategorized materials are grouped in *tbd*.

The building consists mainly of the material categories concrete, timber, stone, and steel, as well as uncategorized materials in tbd (most because they are modular elements consisting of many materials). These categories are the most important in terms of embodied emissions, caused directly by their large quantities. On the other hand, plastics, windows, glass, etc. have high emission factors. Quite surprisingly, and in opposition to the timber residential and concrete office building types, the windows have no replacements. This is a methodological choice difference, where the analysts of the different studies have assumed different lifetimes for the windows. Accordingly, this may perhaps not be a realistic assumption, and it complicates comparison and the trustworthiness of the individual studies. Vinyl is the material category with the highest replacement production emissions (B4m) due to its high replacement emission factor. Timber and stone are responsible for most of the transport emissions.

3.5. Concrete swimming hall

Figure 8 and 9 show the results from 1 concrete swimming hall building, where the subparts are divided into building elements and material categories, respectively. The system boundary is only covering '2: Envelope, foundations, and structure'. Transport emissions are not available. There are similarities between the emission profile of this building type and the concrete school building type, since one of the school buildings are part of the same construction project as the swimming hall, and the LCA was performed by the same analysts. '25: Slab structure' is dominating both in terms of quantity and emissions, followed by '22: Superstructure' and '23: Outer walls'. If windows were replaced at the same rate as in the timber residential building type, '23: Outer walls' would have had even higher emissions. Steel is an important material category, but concrete is dominating both quantity and emissions.

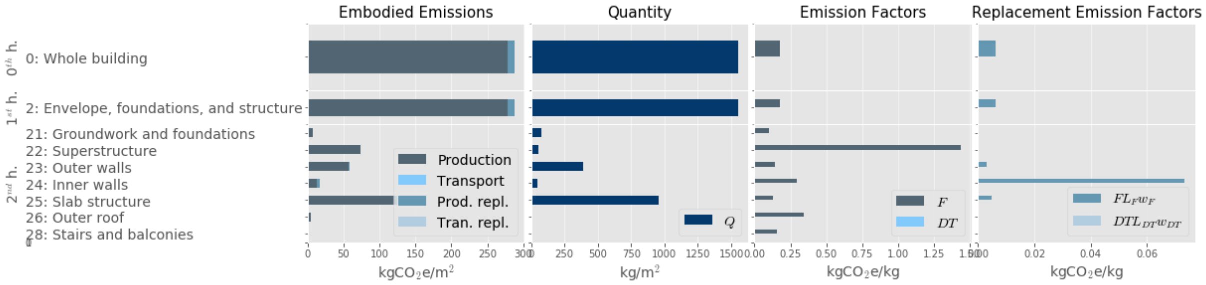

Figure 8. Concrete swimming hall (n=1).

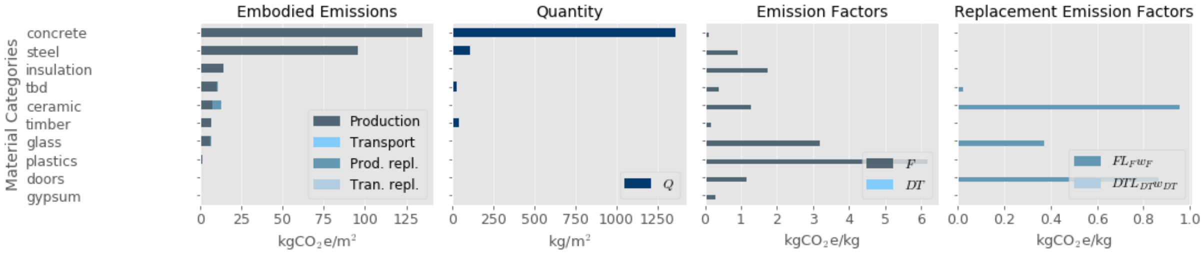

Figure 9. Concrete swimming hall (n=1). Uncategorized materials are grouped in *tbd*.

4. Discussion

The purpose of this paper is to demonstrate a methodology for establishing emission profiles of building types. Such emission profiles can be useful in the early planning phases of construction projects when little information is available about the building, and few decisions have been made regarding the design, material use, and other factors affecting embodied emissions. Furthermore, emission profiles can be useful for policy and strategic planning decisions that influence the future building stock. Finally, emissions profiles is an efficient benchmarking strategy, whereby finalized construction projects can be compared and the emission performance evaluated. A rich dataset is needed to make full use of the method.

Building types can be narrowly or broadly defined, depending on the use case. A building type including a large variety of buildings in a country is useful for establishing a national average. The building types in this paper are specified by main construction material and typology because these two descriptors are expected to influence the final embodied emissions substantially. These building types will then be more useful than a national average for practitioners designing these building types and for decisions made regarding typologies and construction materials. Additional descriptors that affect embodied emissions can be specified to further narrow down the area of application and make the building types representative for specific building cases. These might be dimensional and morphological descriptors such as the number of stories or the floor area, or contextual parameters such as year of construction or a narrowly defined geographical area, or thermal conductivities, ground conditions, or any other descriptor that can be expected to have an influence on embodied emissions. A narrowly defined building type will be better suited for benchmarking a specific building and improvements made towards emission reductions during its design, while a national average building type will be suited to compare and place the building in a broader context. Narrowly defined building types will, however, need large amounts of sufficiently high-quality data with related descriptors. The building LCA database tool described in [8] is tailored for storing and handling this kind of data, and the applications presented in this paper scale seamlessly with additional data added. The limiting factor is the availability of the building LCA data.

In this paper, the emissions from future replacements of materials are reduced by a technological factor for production and another for transport. Taking these reductions into account reduces the importance of future emissions, and underlines the importance of keeping the focus on current and near-future emissions. Besides, future emissions are dependent on many uncertain conditions that are outside of present-day scope of influence. Furthermore, the technological factors show the future emissions from timber buildings to be more affected by technological improvements than for the concrete building types. This is largely due to the more rapid replacement of timber parts than concrete. Future emissions due to replacements are thus much less important than near-future emissions, for timber buildings as well as for concrete.

We have demonstrated how case-specific conditions can have large effects on the emission profiles when the underlying dataset is limited. These initial results are a demonstration of the methodology, which needs to be updated with a larger dataset of building LCAs. The sample sizes are too small to draw conclusions about building types from the results. The differences between the building types are likely to a considerable degree explained by differences in system boundaries and inventory completeness within building elements, as well as case-specific conditions such as ground conditions. One such case-specific condition is the unstable ground conditions for the concrete office, leading to higher emissions in Groundwork and foundations, and explaining much of the difference. Nonetheless, the results give an indication of the emission profiles of the four building types in the Norwegian low-carbon building context.

The data quality presented here depends on the data quality of each of the collected studies. When the number of data points is small, low data quality and incomplete or incorrect system boundaries and inventory will have a big impact on the results. As the dataset grows, these limitations will gradually be mitigated by smoothing out individual study limitations. The current dataset has too much variation in system boundaries and inventory completeness to be valid for general conclusions. Although the methods applied in this paper, e.g. separating inventories into building subparts and applying the statistics on the metrics instead of the final aggregated results, is to a large extent mitigating the uncertainties related to these issues, a larger dataset is needed for generalizable and accurate results.

The results in this paper are missing uncertainty which is a major limitation; this should be included in future work for results to be reliable enough to be used for policy measures. When this is in place, emission profiles can be used for setting maximum allowance levels in building code regulations, and carbon taxes or incentives can be based on such benchmarks.

5. Conclusions

This paper presented a method for establishing emission profiles and material use profiles for material production, transport, and replacements, which will be representative for building types when a sufficient dataset is available. This is useful for gaining insights into how emissions are distributed, and to understand the effect of choices made in the early phases of construction projects. Furthermore, emission profiles can be used to establish benchmark values by which the emission performance of buildings can be measured, and to set regulatory limits on the allowed embodied emission levels of building materials, analogous to existing regulations on operational energy performance. The dataset is not sufficiently large to get reliable emission profiles that are representative for these building types, rather, the results are initial indications and a demonstration of the method. Future work includes an expansion of the dataset and the quantification of uncertainties.

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Paper IV

Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock

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RESEARCH AND ANALYSIS

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Temporal analysis of the material flows and embodied greenhouse gas emissions of a neighborhood building stock

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Abstract

Low-energy building standards shift environmental impacts from the operational to the embodied emissions, making material efficiency (ME) important for climate mitigation. To help quantify the mitigation potential of ME strategies, we developed a model that simulates the temporal material flows and greenhouse gas embodied emissions (GEEs) of the material use in the construction and renovation activities of a neighborhood by combining life-cycle assessment with dynamic material-flow analysis methods. We applied our model on a "zero emission neighborhood" project, under development from 2019 to 2080 and found an average material use of 1,049 kg/m^2, an in-use material stock of 43 metric tons/cap, and GEEs of 294 kgCO$_2$e/m^2. Although 52% of the total GEEs are caused by material use during initial construction, the remaining 48% are due to material replacements in a larger timeframe of 45 years. Hence, it is urgent to act now and design for ME over the whole service life of buildings. GEEs occurring far into the future will, however, have a reduced intensity because of future technology improvements, which we found to have a mitigation potential of 20%. A combination of ME strategies at different points in time will best mitigate overall GEEs. In the planning phase, encouraging thresholds on floor area per inhabitant can be set, materials with low GEEs must be chosen, and the buildings should be designed for ME and in a way that allows for re-use of elements. Over time, good maintenance of buildings will postpone the renovation needs and extend the building lifetime.

KEYWORDS
building material, circular economy, decision support, industrial ecology, life cycle assessment (LCA), material efficiency

1 | INTRODUCTION

The global greenhouse gas (GHG) emission outcomes of current nationally stated mitigation ambitions as submitted under the Paris Agreement are not sufficient to limit global warming to 1.5°C. Deep emission reductions in all sectors and rapid, far-reaching, and unprecedented changes in all aspects of society are required to reach these targets (IPCC, 2018). In 2014, buildings used 32% of global final energy and were responsible for 19%

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of global GHG emissions. Industries were allocated 32% of global GHG emissions, with 11% as indirect emissions (Lucon et al., 2014). The bulk of these emissions are attributed to the processing of materials into products, and close to half of these emissions are due to iron, steel, and cement production, materials that are very much present in the built environment (Heeren, Jakob, Martius, Gross, & Wallbaum, 2013; Müller et al., 2013; Stephan & Athanassiadis, 2017).

GHG emissions from the construction industry are traditionally caused mainly by the energy consumed in the use phase of buildings; however, with an increased focus on highly energy-efficient building concepts, such as low-energy and zero-emission building technologies, the GHG embodied emissions (GEEs) of materials may cause as much as 60–75% of total GHG emissions over the building lifetime (Kristjansdottir et al., 2018). This calls for a stronger focus on material-efficiency (ME) strategies in future building design work.

However, the importance of material use in buildings is still overshadowed by policies focusing on energy efficiency and low GHG emissions energy supply (Scott, Roelich, Owen, & Barrett, 2018). A pluralistic ME-oriented approach that englobes stronger policy drivers for the use of low GEEs materials and increased material reuse is key for a quicker transition to low GHG emissions built environment (Pomponi & Moncaster, 2016).

ME means providing material services with less material production and processing (Allwood, Ashby, Gutowski, & Worrell, 2011). ME can be measured by quantifying material use by the total weight of materials or in service units to provide human needs such as housing or recreation as well as environmental impact-based indicators (Zhang, Chen, & Ruth, 2018) such as in strategies for climate-change mitigation (Hertwich et al., 2019). Demand-side ME strategies are complementary to those obtained through the decarbonization of our energy system and may offer substantial GHG mitigation potentials (UNEP, 2019). Better ME can be achieved through strategies such as (a) more intensive use, (b) lifetime extension, (c) light-weighting, (d) reuse of components, (e) recycling, upcycling, and cascading, and (f) improving yield in production, fabrication, and waste processing (Hertwich et al., 2019).

The potential of the building sector stands out compared to other sectors where climate-change mitigation strategies are more difficult to achieve (Edenhofer et al., 2014). ME strategies such as reusing steel, reviewing the amount of materials used in buildings and the frequency of replacement, reducing the use of cement, reusing concrete in constructions, and extending the lifespan of buildings and infrastructure, all offer tremendous climate mitigation potentials for the built environment (Eberhardt, Birgisdottir, & Birkved, 2019b; Fischedick et al., 2014; Malmqvist et al., 2018; Wiik, Fufa, Kristjansdottir, & Andresen, 2018). Planning authorities, major clients, developers, and individual designers are important to encourage innovative approaches to further reduce GEEs (Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, & Birgisdottir, 2019).

Because emissions from old building stock cohorts are dominated by operational energy use (Sartori & Hestnes, 2007), a common focus has been passive house and low-energy building concepts, such as lowering the total primary energy use below 120 kWh/(m^2·year) (Kylili & Fokaides, 2019). Passive-house design considerably cuts the building energy use, and with additional local renewable energy generation, such as with photovoltaic (PV) or heat pump technologies, to balance out the remaining energy use and life-cycle GHG emissions, nearly or net-zero energy/emissions buildings are possible (Fufa, Dahl Schlanbusch, Sørnes, Inman, & Andresen, 2016; Marszal et al., 2011; Torcellini, Pless, Lobato, & Hootman, 2010). The European Union has set into place the Energy Efficiency Directive (European Commission, 2012) and the Energy Performance of Buildings Directive (European Commission, 2010) that states that all new buildings by 2020 shall be nearly zero-energy buildings (Calwell, 2010).

According to IEA and UNEP (2018), building envelope measures and improvements in the performance of building energy systems have all helped to offset the effects of population and floor-area growth globally, but floor area has the largest influence on energy growth. As floor area increases, not only energy use but also resource use goes up, more land is occupied, and increased impermeable surface results in more storm-water runoff (Wilson & Boehland, 2005). Energy specifications shall not only be given in terms of energy efficiency but complemented by energy sufficiency in terms of a maximum amount of primary energy for a given service, for example, energy need for a building of a certain type for a household of a certain size over a determined period (Calwell, 2010).

Life-cycle assessment (LCA) is a standardized method (ISO 14040, 2006; ISO 14044, 2006) frequently used to estimate how potential environmental impacts accumulate over the different lifecycle phases and elements of a system (Finnveden et al., 2009; Hellweg & Canals, 2014). LCA is increasingly used to evaluate the environmental performance of buildings and neighborhoods (Lausselet, Borgnes, & Brattebø, 2019; Lausselet, Ellingsen, Strømman, & Brattebø, 2020; Stephan, Crawford, & de Myttenaere, 2013) and is the preferred method for quantifying direct and embodied building-related GHG emissions (Zhao, Zuo, Wu, & Huang, 2019).

Previous LCAs on residential buildings with conventional energy standards showed that the total lifetime GHG emissions are dominated by the use phase, with 80–90% of the total (Abd Rashid & Yusoff, 2015; Heeren et al., 2015; Sharma, Saxena, Sethi, Shree, & Varun, 2011). Anderson et al. (2015) attributed 15% to the embodied energy from the production of materials and only some 1% to energy from construction, demolition, and transportation stages. The magnitude of the different life-cycle phases is driven by the building's energy use, the emissions intensity of the energy carriers, and the GHG gas embodied emissions (GEEs) of construction materials (Dahlstrøm, Sørnes, Eriksen, & Hertwich, 2012). In most of the cases, buildings with low-energy-use standards, such as zero-emission buildings (ZEBs), have lower GHG emissions from the operational phase, but higher GEEs from building materials than conventional buildings. For ZEBs, the share of GEEs from materials is found to be from 55% to 87% of the total lifetime GHG emissions (Kristjansdottir et al., 2018; Wiik, Fufa et al., 2018).

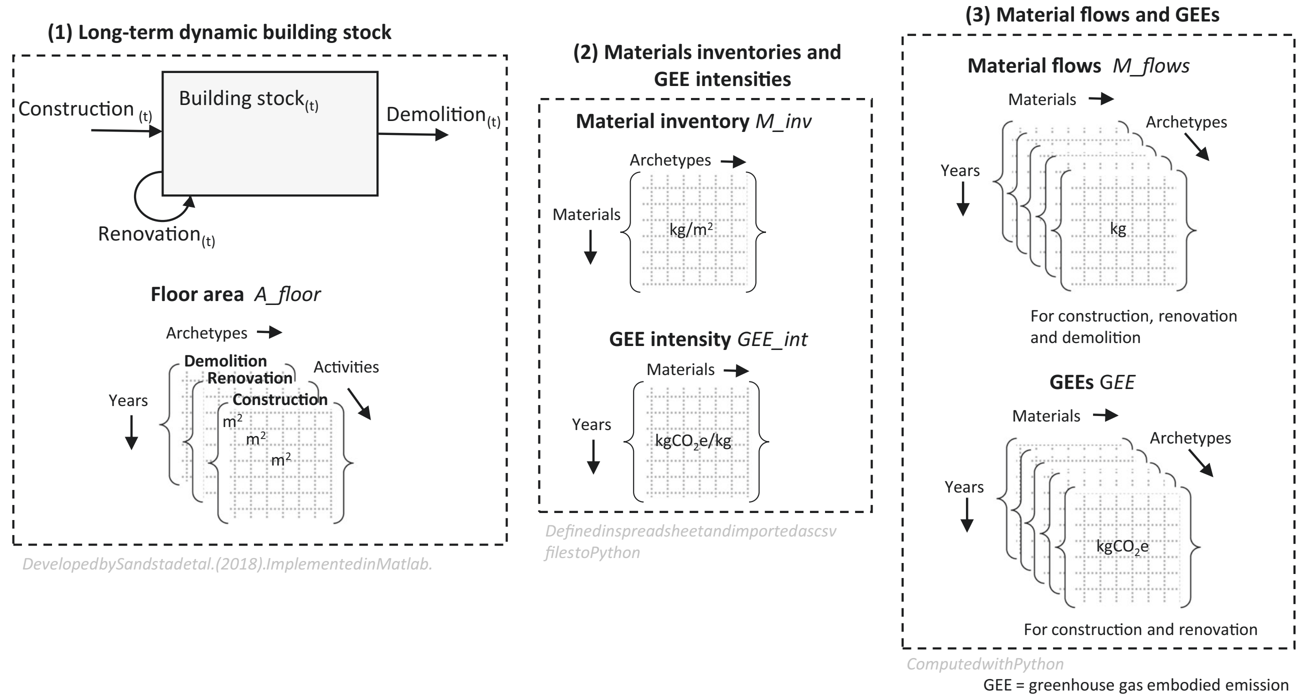

FIGURE 1 Model description

When widening the scope from a building to the scale of a neighborhood, city, country, or region, material flow analysis (MFA) is a well-suited method to determine the material flows and stock of the built environment. Likewise, dynamic MFA (DMFA) can describe the temporal aspects of the historical (Athanassiadis, Bouillard, Crawford, & Khan, 2017; Sandberg, Sartori, Vestrum, & Brattebø, 2016) or future (Sandberg, Sartori, Vestrum, & Brattebø, 2017) evolution of a building stock, the effect of energy-reduction strategies (Ostermeyer, Nägeli, Heeren, & Wallbaum, 2018; Pauliuk, Sjöstrand, & Müller, 2013; Sandberg et al., 2016; Vásquez, Løvik, Sandberg, & Müller, 2016), future material inflow and outflow, as well as the related environmental impacts (Brattebø, Bergsdal, Sandberg, Hammervold, & Müller, 2009; Heeren & Hellweg, 2019; Müller et al., 2013; Pauliuk et al., 2013).

Although considerable efforts have been focused on understanding the energy dimension of buildings, efforts to reduce GEEs from the production of materials, construction, maintenance, and end-of-life stages of buildings require more attention (Lotteau, Loubet, Pousse, Dufrasnes, & Sonnemann, 2015). Also, whereas the literature regarding building material stock and flow dynamics is rich (Lanau et al., 2019), the role of ME strategies and building-specific decisions, such as apartment size or material choice, is less understood (Heeren & Hellweg, 2019). More accurate estimates of material intensities and lifetimes can be achieved by local case studies, and cross-cutting modeling frameworks such as combining MFA and LCA can help capture the environmental impact of materials use (Augiseau & Barles, 2017). Hence, these are also promising modeling approaches to explore the temporal GHG emission power of ME strategies.

To better understand the effects of decisions taken in the early planning phase of a neighborhood, we developed a combined DMFA-LCA model that estimates the GEEs from construction, renovation, and demolition activities of a neighborhood over a 60-year time horizon. The model was applied to the Norwegian zero-emission neighborhood (ZEN) project Ydalir to answer the following questions: (a) Which materials dominate material flows during construction, renovation, and demolition activities over time? (b) Which materials contribute the most to total GEEs during construction and renovation activities? and (c) What are the GEEs mitigation potentials of selected ME strategies?

2 | METHOD

The combined DMFA-LCA model consists of three parts: (a) simulating the long-term building stock of the neighborhood by determining the amount of annual construction, renovation, and demolition activities, (b) setting up the material inventories that characterize each archetype of the building stock and determining the annual GEE intensities for each material, and (c) combining (a) and (b) to calculate the material flows and GEEs over the 60-year time horizon.

The model is conceptually illustrated in Figure 1 and explained in detail in the following sections.

2.1 | Model

2.1.1 | Long-term dynamic building stock

For the long-term dynamic building stock modeling, see part 1 in Figure 1, we use a recent model developed by Sandstad et al. (2018), which simulates the long-term dynamic development of a building stock at national or local scale such as a neighborhood. The model is based on the principles of MFA (Brunner & Rechberger, 2004) as described in Equation (1).

$$BS_{(t)} = BS_{(t-1)} + \Delta BS_{(t)} \tag{1}$$

The building stock BS at year t is equal to the stock of the previous year plus the change in building stock $\Delta BS_{(t)}$ in year t. $\Delta BS_{(t)}$ is the difference between new construction and demolition activities in year t. The model is construction-driven and has the number, type, and floor area of the different buildings to be constructed as yearly model input parameters. The building stock is categorized by archetypes defined by a building type, cohort, and renovation state, such as single-family houses (SFHs) from the 1970s after standard renovation. The timing of future renovation and demolition activities is modeled by a Normal probability distribution. During each building lifetime, demolition can occur once whereas renovation activities can occur several times.

This part of the model is implemented in Matlab with input from spreadsheets. The model output is the yearly stock of the building floor area in m^2, of each archetype stored in the floor area matrix *A_floor* with dimension (year, archetype, activity). Construction and renovation activities are inflows and have positive values. The demolition activities are outflows and have negative values.

2.1.2 | Material inventories and greenhouse gas embodied emission intensities

The second and third parts of the model are implemented in Python with input from spreadsheets. The two Python codes can be downloaded from Github (https://github.com/jpfu9/DYN_EM_MAT-Buildings). A material inventory that contains the amount and lifetime of each material is set up for each archetype. The inventories are structured according to the classification of building elements from the Norwegian standard NS 3451:2009 (Standard Norge, 2009), for example, groundwork and foundations, superstructure, outer walls, and floor structure. The life-cycle system boundary definition follows the European standard EN 15978 (European Committee for Standardization, 2012), in which life-cycle phases are divided into modules A–D, with submodules A1–A3 (production of building materials, cradle-to-gate) and B4 (replacements of building materials throughout the building lifetime/study period). Other modules related to materials in EN 15978 are not included in our model, that is, A4 (transportation of building materials to the building site), A5 (construction), C1–C4 (end-of-life management), and D (benefits outside the system).

The inventories for renovation activities are estimated from the construction inventories material lifetimes. The mass of material inventories in kg/m^2 are given in the material inventory matrix *M_inv* with dimension (material, archetype), see in Supporting Information, S1.

The material inventories contain 78 materials with data taken from environmental product declarations (EPD), which are further classified into 12 material categories: concrete, energy system, glass, gypsum, membrane, mineral, insulation from minerals, insulation from polystyrene, steel, technical, wood, and others.

Each material data point from the EPDs is assigned an equivalent from Ecoinvent (3.2 – cut-off allocation method) (Wernet et al., 2016). The exhaustive list of the 78 materials from EPDs, their Ecoinvent equivalent, and their further classification in the 12 material categories are given in Supporting Information, S3.

For the baseline scenario, Ecoinvent (3.2 – cut-off allocation method) is used for background data and Recipe v1.12 (hierarchist perspective) is chosen for the GWP100 midpoint category (Goedkoop et al., 2013). Other impact categories are not included in the present study, because it is part of the ZEN Research Centre that has its main focus on GHG emissions from neighborhoods.

2.1.3 | Material flows and greenhouse gas embodied emissions

In part 3 of the model, see Figure 1, *A_floor* is multiplied element by element by *M_inv* for each archetype to obtain the matrix of material use *M_flows* in kg/m^2 with dimension (year, material, archetype, activity), as shown in Equation (2).

$$A\_floor \cdot M\_inv = M\_flows \tag{2}$$

TABLE 1 Archetype definition according to the cohort, building type, and renovation state

Cohort	Building type	Archetype name	Renovation state	Activity	Probability distribution function
(1) 2019–2020	Kindergarten	Kind_C	Original	Construction	Not demolished
		Kind_R1	1st renovation	Renovation	N ~ (30,2)
		Kind_R2	2nd renovation	Renovation	N ~ (30,2)
	School	School_C	Original	Construction	Not demolished
		School_R1	1st renovation	Renovation	N ~ (30,2)
		School_R2	2nd renovation	Renovation	N ~ (30,2)
	SFH	SFH2019_C	Original	Construction	N ~ (60,5)
		SFH2019_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2019_R2	2nd renovation	Renovation	N ~ (30,5)
(2) 2021–2025	SFH	SFH2021_C	Original	Construction	N ~ (60,5)
		SFH2021_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2021_R2	2nd renovation	Renovation	N ~ (30,5)
(3) 2026–2030	SFH	SFH2026_C	Original	Construction	N ~ (60,5)
		SFH2026_R1	1st renovation	Renovation	N ~ (30,5)
		SFH2026_R2	2nd renovation	Renovation	N ~ (30,5)
(4) 2031–2080	SFH	SFH_new_C	Original	Construction	N ~ (60,5)

Abbreviation: SFH, single-family house.

The matrix of yearly GHG embodied emissions *GEE* in kgCO_2e/year with dimension (year, material, archetype, activity) is obtained by multiplying *M_flows* with the matrix of materials GEE intensity *GEE_int* in kgCO_2e/kg with dimension (year, material), as shown in Equation (3).

$$M\_flows\; GEE\_int = GEE \tag{3}$$

We decided to include the flows of demolition materials in *M_flows*, to compare their magnitude with that of the material flows from other activities. Their GEEs, however, are not accounted for in *GEE* because module C1–C4 and D are outside the system boundaries of this study, and end-of-life technologies many decades into the future are highly uncertain.

2.2 | Case study: ZEN Ydalir

Ydalir is a project currently under development, aiming to become a ZEN. A ZEN is a neighborhood aiming to reduce its direct and embodied GHG emissions toward zero over its analysis period[1] and which is powered by smart and renewable energy sources. The locally produced surplus energy is sent to the grid (Wiik et al., 2018). When examining potential GHG embodied emission reduction effects of ME strategies for Ydalir, this study uses the following functional unit: "To fulfill the housing demand in terms of residential buildings for the 2,500 inhabitants of Ydalir, including a school and a kindergarten, for a timeframe of 60 years starting in 2019."

The building stock at Ydalir, when the project is fully developed, includes a school of 6,474 m^2, a kindergarten of 2,140 m^2, and 625 SFHs, each with four inhabitants and a total floor area of 100,000 m^2. The main structural material in all the buildings is wood, and the SFHs have photovoltaic (PV) solar panels on their roofs to generate on-site renewable electricity. The school and kindergarten were built in 2019, and the SFHs are to be constructed evenly from 2019 to 2030. The buildings are identified according to their year of construction, with four cohorts: "2019 to 2020," "2021 to 2025," "2026 to 2030," and "2031 to 2080."

The combination of the cohort, building type, and renovation state results in 16 archetypes; 6 construction archetypes and 10 renovation archetypes, as defined in Table 1.

The building type SFH_new_C in cohort 4 is included to ensure a constant floor area over the 60-year analysis period, despite demolition activity toward the end of the period; hence, the yearly floor area in this cohort mirrors the amount of floor area demolished for the same year.

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[1] The analysis period of a ZEN project may depend on the objective of the study. The ZEN definition referred to for Norway recommends 60 years analysis period for a ZEN project, with 60 years service life of buildings and 100 years service life of infrastructure.

The demolition activities of the SFHs follow a normal distribution with 60 years as mean service life and with a standard deviation of 5 years. The school and kindergarten are not assumed to be demolished in the studied timeframe.

The renovation activities of the SFHs are normally distributed with 30 years as a mean renovation frequency and with a standard deviation of 5 years. A shorter standard deviation of 2 years is used for the school and kindergarten because it is expected that these will be renovated close in time.

The mean value of renovation activities, 30 years, is assumed on the basis of the expected average material lifetime before replacement because of renovation, for building elements that will be replaced during a 60-year analysis period. Under these assumptions, and with renovation activities following a Normal distribution, two renovation activities can occur for a share of the buildings. The material inventories for the first and second renovations are almost similar, with some material increase in the second renovation, because of the replacement of some building materials with a lifetime greater than 30 years that are not replaced in the first renovation. See Supporting Information S1 for the complete lists and lifetime of material for each archetype.

2.3 | Material efficiency scenarios

A total of eight ME scenarios are established to examine three of the ME strategies reviewed by Hertwich et al. (2019). The two last scenarios test the uncertainty range by setting the GEE intensities to the lowest and highest possible values for each material category. The ME scenarios are described in Table 2.

3 | RESULTS

Construction and renovation activities at ZEN Ydalir mobilize a total of 116 kton of materials with 82.6 ktonCO$_2$e between 2019 and 2080, equivalent to an average material use of 1,049 kg/m^2, in-use stock of 43 tons/cap, and GEEs of 294 kgCO$_2$e/m^2. The initial construction activities drive most of the material use and GEEs. The most dominant material flow is concrete followed by wood. The most dominant source of GEEs is the PV panels, followed by wood and concrete.

In the following sections, the dynamics of the floor area, material, and GEEs flow of the building stock of Ydalir are described, followed by the results from the ME scenarios.

3.1 | Floor area dynamics

The floor area dynamics are presented in Figure 2. The initial construction activities take place during the 11 first years from 2019 until 2030. The kindergarten and the school were built in 2019, and the residential SFHs are built uniformly from 2019 until 2030.

The first renovation activities of the SFHs start in 2035 with some renovation from the first cohort. The renovation activities increase in the 2040s when the second and third cohorts come into play and peak in the 2050s. Renovations are completed by 2062 for the first cohort, by 2071 for the second cohort, and by 2076 for the third cohort. Because of the assumptions in our study, the school and kindergarten are estimated to undergo their first renovation from 2047 to 2049.

The second wave of renovation begins in the mid-2060s and overlaps with the first wave, and some renovation activity therefore occurs every year after 2035. For SFHs, it peaks around the end of the study period, and for the school and kindergarten, it occurs between 2076 and 2078. By 2080, 43% of the SFHs from the first cohort are renovated, and 32% and 12% from the second and third are renovated, respectively. In total, 32% of the neighborhood's building stock has undergone a second renovation in 2080.

Demolition is estimated to begin in 2064, for SFHs of the first cohort. By 2080, the demolished area accounts for 25,600 m^2 or 24% of the initial building stock, and the new construction is equivalent to 160 new SFHs, out of 625 SFHs in total.

3.2 | Material and embodied emissions intensities by archetype

The material intensity for each archetype and material category is shown in Figure 3a.

The construction of the kindergarten and the SFHs have a similar material intensity of 743 kg/m^2 and 731 kg/m^2. The school has a material intensity of 1,024 kg/m^2, which is 40% higher than the kindergarten and the SFHs, mainly because of higher material use in the groundwork and foundation (concrete, wood, and minerals such as asphalt). Among all archetypes, concrete and wood represent 63–89% of the material requirement in construction activities: concrete with 57–64%, wood with 18–32% followed by gypsum with 3–7%, and mineral, glass, energy system, and

TABLE 2 Material efficiency (ME) scenarios

ME strategy[a]	Scenario	Description	Single-family house size (m^2) 160	Single-family house size (m^2) 120	Building lifetime[b] (year) 60	Building lifetime[b] (year) 100	Renovation rate (year) 20	Renovation rate (year) 30	Renovation rate (year) 40	Ecoinvent	EPD
	Baseline	Single-family house of conventional size and lifetimes according to standard	+		+			+		+	
(1) More intensive use	S1-30 m^2/cap	The SFH floor area is reduced by 25% from 160 m^2 to 120 m^2 in line with a residential floor area per capita of 30 m^2 proposed by Grubler et al. (2018). The material inventories are downscaled linearly.		+	+			+		+	
(2) Lifetime extension	S2-Ren40	The mean renovation period is set to 40 years for all the buildings. This scenario forces the renovation to happen less often, and test for the effect of a material lifetime extension.	+		+				+	+	
	S3-Ren20	The renovation rate value is decreased and set to 20 years for all building types to test for the opposite effect of S2-R40.	+		+		+			+	
	S4-Con100	The lifetimes of all the buildings are extended and set to 100 years.	+			+		+		+	
(3) Improving yield in production	S5-Ecoinvent 40%	Improving yield in production has a direct effect on the materials' emission intensities. A linear decrease of the emission intensities by 40% from 2019 to 2050 is assumed, based on technological factors proposed by Resch, Lausselet et al. (2020).	+		+			+		(+)	
	S6-EPD	Emission intensities are replaced with values from Environmental Product Declarations (EPDs) representative for Norge where the electricity mix is highly decarbonized.	+		+			+			+
Combining strategies	S7-30 m[b] /cap +Ren40	This scenario combines two ME strategies; (1) more intensive use as in S1 with (2) lifetime extension of material through increased renovation rate as in S2.		+	+				+	+	
	S8-30 m^2/cap +Ren40+EPD10%	This scenario combines all the ME strategies in addition to a decrease of 10% in the material emission intensities.		+	+			+			(+)
Uncertainty	S9-High	The material emission intensities are replaced with the highest values inside each material category	+		+			+		+	+
	S10-Low	The material emission intensities are replaced with the lowest values inside each material category	+		+			+		+	+

[a] The scope is limited to three ME strategies, but other ME strategies could have been implemented such as "light-weighting" by updating the detailed material inventories or "reuse of components" and "recycling, upcycling, and cascading" by using the annual material outflows.

[b] The standard deviations remain unchanged.

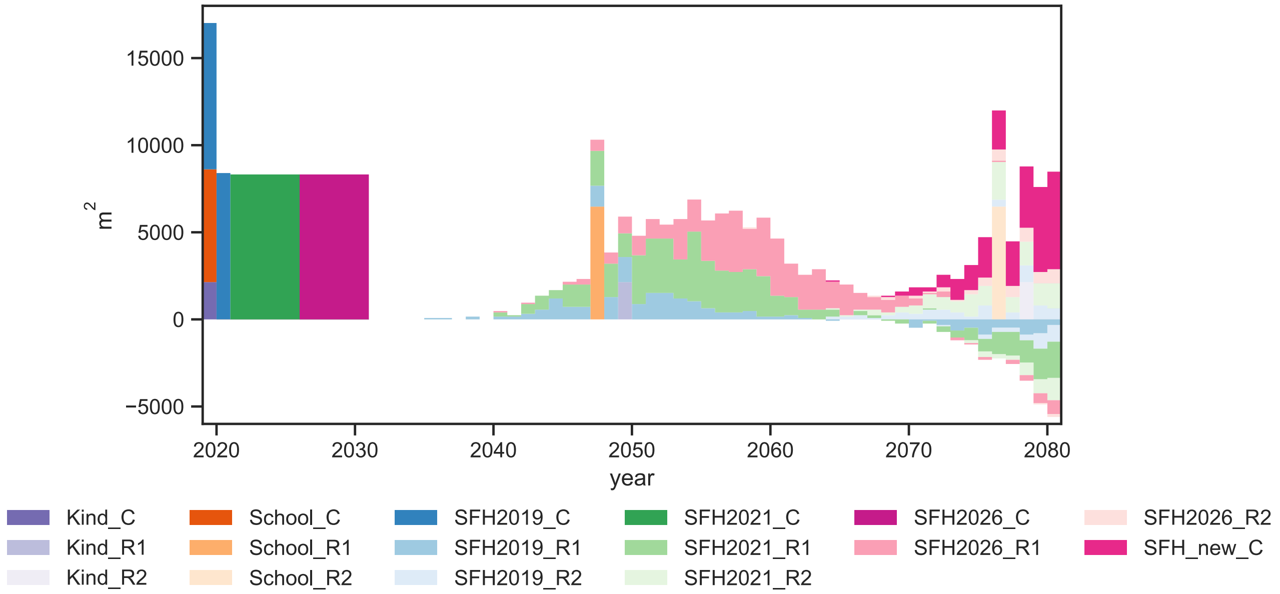

FIGURE 2 Construction, renovation, and demolition of floor area (*A_floor*) in the neighborhood over the years. Underlying data used to create this figure can be found in Supporting Information S2

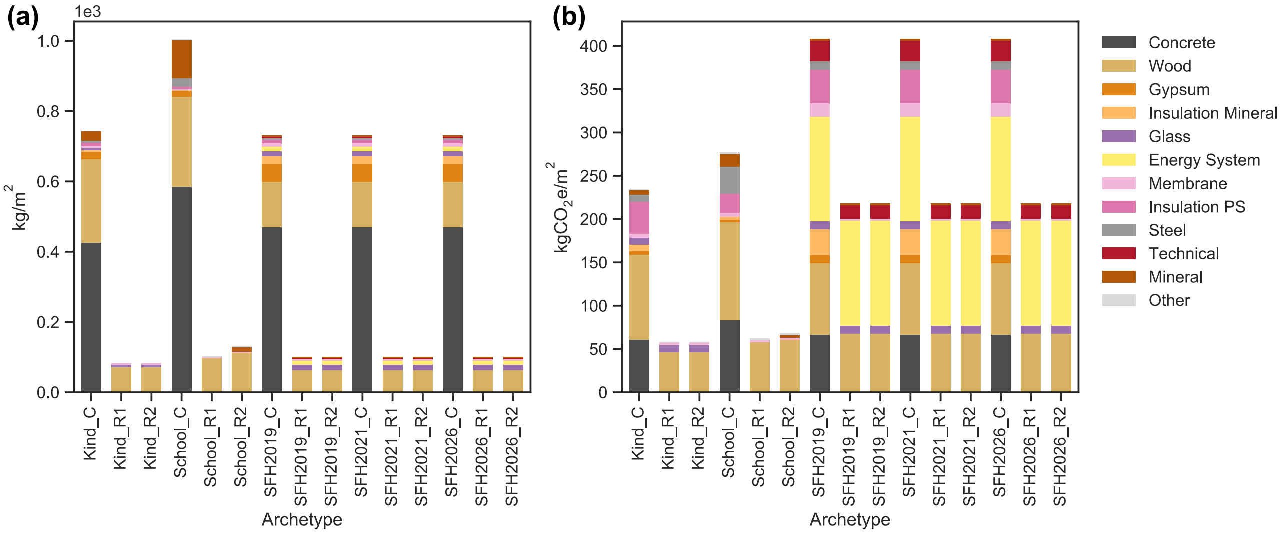

FIGURE 3 (a) Material intensity per m^2 per archetype; (b) emission intensities per m^2 per archetype. Underlying data used to create this figure can be found in Supporting Information S2

membrane with only marginal shares. The renovation of the kindergarten, school, and SFHs requires an additional 11%, 10%, and 14% of the material quantity used in the construction, respectively. Wood is the main material being replaced.

The GEE intensities of the 15 first archetypes are shown in Figure 3b. In the construction phase, the kindergarten is the least emission-intensive with 234 kgCO$_2$e/m^2, followed by the school with 277 kgCO$_2$e/m^2 and the SFHs with 408 kgCO$_2$e/m^2. In the renovation phases, the GEE intensities of the kindergarten, school, and SFHs are respectively 25%, 23%, and 53% of their construction.

The GEE intensities of the construction and renovation activities are highest for the SFHs because of the emission contribution of the PV panels installed on the roofs (part of Energy System), accounting for 30% of their total GEEs in the construction and 56% in the renovation.

3.3 | Material and embodied greenhouse gas emissions storylines

The neighborhood material and GEEs storylines are presented in Figure 4, expressed by their absolute (Figures 4a and 4b) and cumulative (Figures 4c and 4d) material and GEEs flows per material category.

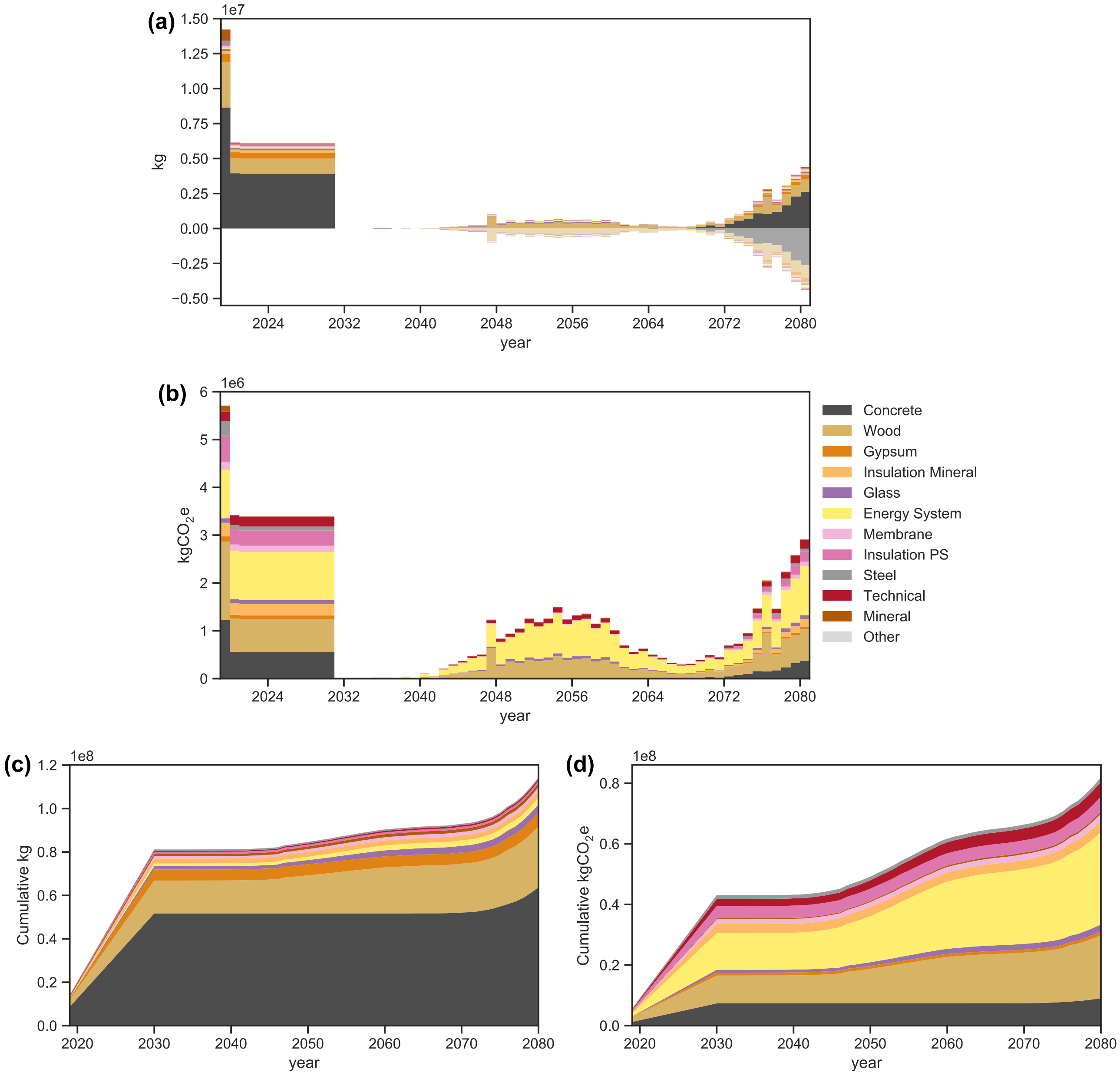

FIGURE 4 (a) Yearly material; (b) greenhouse gas embodied emissions (GEEs); (c) cumulative material flows by material categories; (d) GEEs flows by material categories. Underlying data used to create this figure can be found in Supporting Information S2

A total of 114 kton material is needed to construct, renovate, and maintain the neighborhood's building stock floor area: 71% for the construction, 13% for the renovation, and 16% for the new construction required to maintain the building stock floor area constant over time.

Rapid material stock accumulation occurs in the first 11 years. After 2030, the material stock accumulation remains almost constant until around 2045, when the first renovation activities start. The flow of concrete and wood dominates the material flows over the years, with 55% and 25% of the total material flows, respectively.

A total of 82 kton CO_2e is emitted, equivalent to 294 $kgCO_2e/m^2$. 52% of the total GEEs are due to the initial construction activities, 36% are due to the renovation activities, and the remaining 12% are due to the new constructions at the end of the analysis period. Although the GGEs from initial construction activities are fairly similar to those from the later renovation and new construction activities, the time window in which they occur is different. Whereas 52% of the total GEEs are spread in the first 11 years (2019 to 2030), the remaining 48% occur in a distant timeframe of 45 years (2035 to 2080). Note that the results here are for our baseline scenario, in which constant GEE intensities over time are assumed. The GEE intensities are likely to decrease during future decades, as a result of technology improvements in materials production (Gibon et al., 2015; Wiebe, Bjelle, Többen, & Wood, 2018) and low-carbon electricity generation (IEA, 2015). The magnitude of such changes is hard to predict and therefore highly uncertain. However, we explore the effects of changing GEE intensities over time in two of our ME scenarios, see results in the section below.

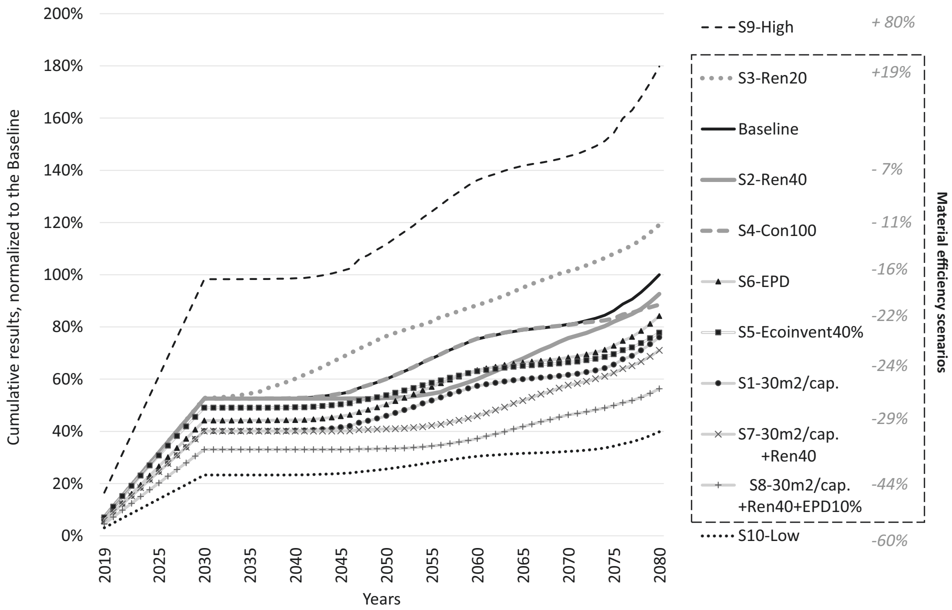

FIGURE 5 Cumulative greenhouse gas embodied emissions (GEEs) for all the scenarios. Underlying data used to create this figure can be found in Supporting Information S2

The cumulative GEEs are dominated by PV panels in the energy systems, contributing to 37%, followed by wood 30%, concrete 11%, and insulation-PS 5%. Wood takes up a third of the emissions because it is the main structural material; the results should therefore not be interpreted as wood being worse than concrete in general but as a typical current Norwegian neighborhood project consisting of wooden buildings only.

3.4 | Material efficiency scenarios

The results of the eight ME and the two uncertainty scenarios are presented in Figure 5 relative to the baseline scenario. The results of the ME scenarios show GEEs mitigation potentials ranging from 7% to 44%. The two uncertainty scenarios S9 and S10 show that the choice of another GEE intensity for the same material will largely influence the cumulative GEEs, from a 60% decrease in S10 to an 80% increase in S9.

The construction activities induce rapid GEEs increase with a peak in 2030, which accounts for about half of the cumulative GEEs for all scenarios along the study period. The magnitude of the construction peak can be reduced by 9% by implementing ME strategies that improve the yield in the production of the building materials (S6), by 13% by a more intensive use (S1) and up to 20% (S8) by combining the two aforementioned strategies.

From 2035, the GEEs are induced by renovation activities and new construction of SFHs at the end of the analysis period. Those future GEEs can be mitigated by several ME strategies. Improving the material lifetime by postponing renovation activities (S2) has a mitigation potential of 7%. The introduction of more intensive use of the buildings, by introducing a maximum floor area per capita design criterion in the neighborhood planning stage, will also have a direct multiplier effect on the stock to renovate, with a mitigation potential of 11% (S1). The same potential is obtained by increasing the building's lifetimes to 100 years, thus avoiding the need for new construction at the end of a 60-year analysis period. To factor in the improved yield in material production over time gave a mitigation potential of 18% (S5). The best mitigation potential of the GEES after 2035 is 24% and is achieved by combining all ME strategies (S8).

The combination of different ME strategies also shows the highest mitigation potential of the cumulative GEEs. Combining a more intensive use of buildings with a higher material lifetime (S7) has a cumulative mitigation potential of 29%, whereas a further combination of the former scenario with an improved yield in material production leads to further mitigation of 15% for a total of 44% (S8).

Concerning the development of the GEES over time, all ME scenarios go through a GEEs plateau after the construction peak in 2030 until the renovation activities start. The scenario with earlier renovations (S3) finishes 19% above the Baseline scenario, demonstrating the unwanted effect of high renovation frequencies. The scenario with increased material lifetime (S2) decreases its progression rate because the renovation activities are postponed. The effect of the first renovation can be seen around 2045 for the scenarios following conventional renovation times (Baseline, S1, S4, S5, and S6). The slopes of the scenarios where ME strategies improve the material production yield (S5 and S6) is less steep than the slopes of the scenarios where this type of ME is not implemented (S1 and S4).

The effect of a longer building lifetime comes into play around 2070 when the need for the construction of new SFHs to maintain the functional unit constant over the analysis period starts. For that reason, the baseline and S4 scenarios that follow the same renovation rates split at this point.

4 | DISCUSSION

4.1 | Comparison with other studies

The baseline GEE intensity of 294 kgCO2e/m^2 of the Ydalir project, with an uncertainty ranging from 118 to 529 kgCO2e/m^2, is in line with previous studies. For the same geographical context and modules A1–A4 and B4, Kristjansdottir, Heeren, Andresen, and Brattebø (2018) found GEE intensity of low-energy and zero-emission SFHs to range from 252 to 282 kgCO$_2$e/m^2, and Wiik, Fufa et al. (2018) reported values for seven residential and non-residential zero-emission building case studies from 282 to 918 kgCO$_2$e/m^2. The International Energy Agency Energy, in Building and Communities Annex 57, analyzed over 80 building case studies and found building materials GEEs to range between 20–620 kgCO2e/m^2 for construction (module A1–A3), and 20–180 kgCO$_2$e/m^2 for replacement (module B4). Although reported process-based LCA results went up to a value of 620 kgCO2e/m^2 for modules A1–A3, input-output based results can reach even higher up to 1,100 kgCO2e/m^2 (Moncaster et al., 2019). This is well beyond the figures we found for Ydalir and underlines the importance of regional building technologies, material choice, and system boundaries in LCAs for building stock GEE analysis.

For all scenarios, we found concrete and wood to dominate both the material flow and the GEEs. This is fully in line with what is recently reported by Resch, Lausselet, Brattebø, & Andresen (2020) and Resch, Brattebø, & Andresen (2020), for the same type of buildings in Norway. For other geographical contexts, concrete, cement, sand, and gravel are in many cases the dominant materials (Heeren & Hellweg, 2019; Huang et al., 2018).

We found a total in-use material stock of 32 tons/cap. For residential buildings, Gontia, Nägeli, Rosado, Kalmykova, and Österbring (2018) reported an in-use material stock for the city of Gothenburg in 2016 of 62 tons/cap. Wiedenhofer, Steinberger, Eisenmenger, and Haas (2015) reported 72 tons/cap for the EU25 in 2009, and Huang et al. (2018) reported 24–25 tons/cap for China. Our results are roughly half of the European results, which is expected because our buildings are wood-based and thus lighter, and slightly higher than the Chinese figures mainly because of less floor area per inhabitant in China.

4.2 | Material recycling, upcycling, and cascading

The potential to reuse and recycle materials in the building sector is well present (Augiseau & Barles, 2017; Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). For Ydalir, 13% and 16% of material flows are from renovation and demolition activities. The material outflows could be further examined regarding their mitigation potential if exposed to recycling, upcycling, and cascading ME strategies, according to the principles of a circular economy. Also, the design of buildings should consider solutions that facilitate the disassembly of materials to allow for such strategies (Eberhardt, Birgisdóttir, & Birkved, 2019a; Malmqvist et al., 2018).

4.3 | Alternative life-cycle inventory techniques

Although the use of different process-based LCA background databases (EPDs and Ecoinvent 3.2) has been tested, the use of other LCI techniques that use wider system boundaries for the inventory of materials should also be examined because this might significantly influence the results (Crawford, Bontinck, Stephan, Wiedmann, & Yu, 2018). Whereas process-based LCIs suffer from truncation errors, input-output LCIs suffer from aggregation uncertainties (Lenzen, 2000; Majeau-Bettez, Strømman, & Hertwich, 2011). The use of hybrid LCIs may provide a more comprehensive analysis of a product system, and the recent efforts by Agez et al. (2020) and Stephan, Crawford, and Bontinck (2019) to streamline hybrid LCI by automating various components will help their uptake by a wider community.

4.4 | Importance of infrastructure-related emissions

In addition to buildings, construction materials accumulate in infrastructure elements of a neighborhood, such as road networks, drinking water, wastewater, heat supply, and gas-pipe networks. Such elements can account for substantial shares of the total in-use material stock of built environment and have been reported to account for 38% and 1.3% for roads and wastewater pipes, respectively, in Gothenburg (Gontia et al., 2018), 53% for roads in the EU25 (Wiedenhofer et al., 2015) and 26%, 19%, and 8% for roads, seaports, and dams, respectively, in Japan (Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). The related GEEs profile of infrastructure is region-specific and directly related to the level of economic development. Typically, it was approximately five times larger for industrialized countries compared to developing countries in 2008 (Müller et al., 2013). According to these figures, our study for Ydalir is potentially missing a significant share of the total built in-use material stock and their related GEEs, even though this project is by purpose designed with very little internal infrastructure demand.

4.5 | Strengths and limitations

The main strength of our model is its ability to combine long-term temporality in dynamic analysis of construction, renovation, and demolition activities with detailed material life-cycle inventories of buildings. The use of detailed case-specific life-cycle material inventories for individual building types reduces the uncertainty in material-flow estimates and provides more reliable results.

The model's scenarios of future development paths can reveal how GEEs are influenced by parameters describing alternative future developments. Predicting how such parameters will evolve has substantial uncertainty, which was partially explored in two uncertainty scenarios. In reality, a combination of different ME strategies will likely lead to an even larger variation in results. A global sensitivity analysis such as a variance-based sensitivity analysis (Saltelli et al., 2010) can be performed to capture such effects.

The future estimates of material flows and GEEs should not be regarded as predictions, but rather as possible paths that can be influenced. In general, the uncertainty increases into the future, and our results showed the construction peaks to release the majority of the GEEs at the beginning of the neighborhood storyline. Therefore, the main priority should be on design and ME strategies to reduce near-future emissions. Moreover, technological improvement and the decarbonization of the energy mix over that time will decrease the GEE intensity of the production of the materials (Gibon et al., 2015; Lausselet et al., 2020; Resch, Lausselet et al., 2020; Wiebe et al., 2018). We factored in the effects of technological improvements in two scenarios (S5 and S8) and found a reduction of future GEEs of 20%.

The average building lifetime in our model is set to be 60 years, in line with the Norwegian standard NS3720:2018 for the calculation of GHG emissions for buildings and the Norwegian ZEN definition (Wiik et al.,2018). Yet, it seems that a lifetime of as much as 125 years is closer to reality in Norway (Sandberg, Sartori et al., 2016). Given that the analysis period of our study is equal to the assumed building lifetime of 60 years, the implications of longer lifetimes are not fully captured. A building lifetime of 100 years, as depicted in S3, shows that new construction to compensate for demolition activities as well as the third round of renovation would not happen within an analysis period of 60 years because this will start after 2080. Lifetime estimates and renovation frequencies for buildings in a new neighborhood are unreliable and a source of uncertainty in GEEs scenario models. Our results show that different assumptions may significantly influence the annual and cumulative GEEs. A Normal distribution function is used because it is assumed that all the stock is renovated, which may not be the case when using a Weibull distribution (Sartori, Sandberg, & Brattebø, 2016). When used to estimate the building's lifetime, Normal and Weibull distributions have been proven to give similar results (Zhou, Moncaster, Reiner, & Guthrie, 2019).

The archetypes make a distinction between building types and assume the same material requirements for each building within the same building type. Although this approach is adequate for a neighborhood in the early planning phase, a bill of quantity specific to each building should be used in later planning phases, when such information becomes available. Alternatively, the use of a three-dimensional model linked with geographic information system data might be helpful to derive a bill of quantity for each building, as done by, for example, Stephan and Athanassiadis (2018) or Heeren and Hellweg (2019).

4.6 | Further work

The system boundary of our model could be expanded to follow the definition from the ZEN Research Centre, to include neighborhood elements such as mobility, road infrastructure, and energy grids, as done in a previous LCA study for another ZEN, by Lausselet et al. (2019) and Lausselet et al. (2020). To design a ZEN project with minimum GEEs, it is necessary to understand the emission drivers for each element of the neighborhood over time. An estimation of the energy demand and on-site energy generation would also give insights on how much of the GEEs can be balanced by emission credits gained by the excess on-site energy exported to external grids. Buildings and mobility can each account for 40–60% of the total GHG emissions of a ZEN, and a holistic strategy including also mobility should be embraced to help guide local design decisions to minimize GEEs.

4.7 | Strategies and policy implications

Our scenarios have shown that a combination of different ME strategies is the most efficient way to mitigate the GEEs of the assessed ZEN. ME strategies that reduce the floor area per inhabitant are very efficient to reduce the construction peak and its latter multiplier effect on future material flows and emissions. Besides, implementing guidelines that would propose an optimal GEE intensity for a given building type is an appropriate strategy to reduce GEEs of the building stock over time. This strategy will help architects keep their design options following the right GEE intensity target track. The GEE intensities and lifetimes of each material will then be balanced to stay below the recommended target limit.

The predictions of material outflows can be used to identify opportunities to reuse or recycle these resources. The anticipated knowledge of how much and what material flows out at a given time can be used to plan new construction or other activities that may take advantage of those resources. Understanding the evolution of material flows and the related GEEs of a neighborhood over time is useful to tailor strategies that can reduce the GEEs at different points in time and reuse materials on a neighborhood or regional scale.

5 | CONCLUSION

The introduction of low-energy standards in the construction sector shifts the focus from the operational to the construction phase, and this calls for attention on how and when to minimize GEEs. To quantify these GEEs, we developed a model that calculates the material flows and their associated GEEs of building stocks in neighborhoods over time by combining LCA with DMFA methods. The model is applied to the ZEN Ydalir project, in Elverum, Norway.

Scenarios are developed and tested to assess the climate mitigation potential of different ME strategies, and a potential of up to 44% GEEs reduction was found. Further reductions are possible by combining scenarios or making each scenario more aggressive, for example, by use of stronger technology improvements or lower renovation frequencies. Implementing a combination of ME strategies at different points in time will best help mitigate GEEs. In the planning stages, threshold values of floor area per inhabitant can be required, materials with low GEE intensity should be preferred, and the building should be designed in a way that allows for re-use of elements. Over time, good maintenance of the buildings will postpone renovation needs and extend the building lifetime.

The type of dynamic model that is used in this study, with detailed material and GEEs layers, can be used to plan the design of a neighborhood in a way that minimizes total GEEs by exploring the effects of different ME strategies. We found that half of the total GEEs occurs during the first 11 years. This underlines the urgency of a building-design approach that targets GEE reductions in the construction stage of a project. Moreover, with significant GEE also occurring during future decades, because of material replacement in renovation and demolition activities, it is important to avoid unexpected lock-in effects by also adopting a design approach committed to ME strategies over the total service life of buildings. The magnitude of the construction peak, the high uncertainty of future activities, and the predicted technology improvements that will reduce the future material GEE intensity all tell us that the main priority for GEEs reduction in neighborhood projects should be on measures that can strongly influence near-future emissions.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Paper V

Estimating dynamic climate change effects of material use in buildings–Timing, uncertainty, and emission sources

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The paper's context in the thesis:
Temporal modeling combined with a culmination of methods from papers I, II, and III, in addition to the introduction of novel dynamic methods, statistical results, and uncertainty and sensitivity analyses.

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Estimating dynamic climate change effects of material use in buildings—Timing, uncertainty, and emission sources

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ABSTRACT

Material use in buildings affects the climate over centuries, however, temporal aspects are often ignored in Life Cycle Assessment (LCA). Results too often promise uncontested precision of impacts occurring far into the future. Additionally, the validity of building LCAs is being questioned over inadequate scope and inventory.

A dynamic LCA method for material use in buildings that addresses those concerns is presented, along with a case study of 20 buildings. In particular, a novel solution to account for delayed emissions is presented, along with future technological improvements. Climate change effects of material use in construction, operation, and end-of-life phases are estimated, from production, transport, construction-waste incineration, biogenic carbon-sequestration, and cement carbonation. Building subpart metrics reveal drivers of impacts and are used for generating statistical emission profiles.

Application on a bottom-up harmonized dataset produces statistical results for building types (typology, timber/concrete) and building subparts (building elements, material categories). Global warming policy targets requires that the building industry focuses on interventions with short-term effects, such as low-impact materials in the construction phase and reduced construction waste.

Uncertainty is estimated, and parameter influence assessed with global sensitivity analysis. Time horizon (TH), building lifetime, and construction waste parameters are found most sensitive. The method reduces uncertainty of postulated future impacts; an important step in the direction of policy-relevant modeling. We recommend that building LCA modeling practice adopts the presented methodological concepts to gain trust and policy-relevance.

1. Introduction

Buildings are a large global source of anthropogenic greenhouse gas (GHG) emissions, which can be estimated by Life Cycle Assessment (LCA) methods. Results can be used to identify promising mitigation interventions and design improvement strategies, benchmark individual building performance, and guide effective policy measures. With growing focus on material embodied emissions in buildings, GHG emissions are usually quantified in $kgCO_2e$ per unit of material consumed or per m^2 of floor area, according to the 100-year Global Warming Potential (GWP_{100}) indicator and with data from Environmental Product Declarations (EPDs) from given manufacturers. The information from EPDs, together with material quantities and other data specific to the building form the basis for modeling its emission profile throughout its postulated lifetime. However, the validity of building LCAs has been questioned due to varying system boundaries and assumptions, lack of completeness, transparency in methodological choices, and reproducibility [1–3], and for ignoring time-dependent effects [4–7]. There are also large uncertainties that are often not quantified and communicated [8].

1.1. Complexity and uncertainty of LCA modeling

Modeling the environmental impact of buildings is inherently uncertain due to their long service life and large variation in design and composition. Nevertheless, LCA too often promises uncontested precision [8]. Saltelli et al. (2020) [8] offer five principles that society should demand to ensure quality from modeling: Minding the assumptions, hubris, framing, consequences, and unknowns. LCAs of buildings too often ignore those principles, thereby damaging their trust. In general, results of unclear LCAs lack significance and inhibit conclusions that could aid environmental paradigm shifts [3]. We suggest that the principles can be implemented in LCA modeling as follows.

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Assumptions: By exploring the entire parameter space, a global sensitivity analysis (GSA) can determine to which parameters a model is particularly sensitive, and will thereby reveal parameters that demand high confidence. GSA stands in contrast to local sensitivity methods, limited in their ability to quantify how individual parameters contribute to the overall uncertainty [9]. Sensitivity analysis methods best fit for building LCAs were investigated in [10], who found that the most used methods were regression-based or local sensitivity analyses and that the choice of method was rarely justified. The study concluded that the variance-based Sobol analysis was best fit to precisely determine the factors' influence when ignoring its much higher computational cost. Sobol analysis is also able to identify interactions and non-linearities. Using this method, the study found the three most influential parameters to be the building lifetime, the time horizon, and the choice of an hourly versus yearly electricity mix [10].

Hubris: Complexity should only be added to a model if it reduces the overall uncertainty. By determining factors responsible for model variance, less influential factors can be assigned default values while priority is given to the most influential, hence simplifying the model description. Future events are highly uncertain. This should be reflected in the modeling by avoiding superfluous complexity, and the greatest uncertainties should be reduced first.

Framing: The outcome of an LCA highly depends on modeling choices and scenario assumptions [3]. One normative question that can be asked is how to reduce the building's impact on climate change over a defined time horizon (TH). Within a short TH, future emissions will have less time to warm the atmosphere. LCA studies usually consider the impact over the same TH for emissions happening at whatever point in time (for example, construction and dismantling emissions are both assumed to happen at year 0 and their impact assessed with GWP_{100}, i.e. a time horizon of 100 years). According to the IPCC, however, emissions must be cut rapidly if we are to stay within the 1.5 °C and 2 °C targets, making timing highly relevant [11]. Furthermore, if the goal is to reduce the overall impact of a building's materials, the scope must include all relevant materials and emission sources.

Consequences and unknowns: Results of building LCAs are profoundly uncertain; some parts more than others. The degree of confidence should be conveyed when presenting LCA results, to stimulate effective climate mitigation in the construction industry. Likewise, unknowns must be communicated.

1.2. Time-dependent effects

Non-dynamic LCA aggregates GHG emissions over the lifetime and ignores time-dependent effects. For products with long lifetimes, such as buildings, the timing of events will influence both the likely magnitude of future emissions and their aggregated effects over a defined TH. A dynamic LCA (DLCA) can be used to include those effects, but this requires lifecycle inventory (LCI) emission data for each year in the TH, as well as the temporal development of the dynamic effects.

A dynamic LCA framework proposed in [4] was applied in multiple studies, e.g. [4,5,12–14]. Various frameworks for dynamic LCA for buildings were proposed in [6,7,15–19].

The most common application of time-dependent emission effects for buildings is related to carbon sequestration and temporary storage of biogenic carbon in building products. Ref. [20] presents a critical review of the main approaches to include time considerations in LCA of biogenic carbon. Of the different methods available, the dynamic LCA approach [4] is based on a temporal explicit life-cycle emission inventory, which can be produced by using probability density functions (PDFs) to model the timing of future events and distribute future emissions [20]. The use of PDFs to model the decay of carbon-containing products is better suited than the more common first-order decay approaches [21]. In [22], different PDFs were compared and it was concluded that a chi-square distribution, also used in e.g. [23], appears most reliable and appropriate. In a study of the sensitivity of parameters in dynamic LCA, it was concluded that dynamic climate change is not sensitive to LCI time steps lower than 1 year [24]; the difference in results is rather dominated by the choice of TH.

Moreover, future emissions will be affected by technological development. Technological development of material production was implemented in [14], and by a dynamic emission factor for electricity in [15]. The effects of technological progress on material production and transport were investigated by Resch et al. [25], where the future magnitude of emissions were adjusted by the modeled technological improvement in the year of their occurrence.

1.3. The climate change impact of buildings

Several previous studies have presented statistical LCA results, however, they are often based on varying system boundaries and offer no assessment of uncertainty. A global study from International Energy Agency Annex 72 analyzed the carbon footprint of 238 buildings [2]. For advanced building energy-performance classes, the first and third quartiles of embodied emissions range between 0.1 and 0.5 tons CO_2e/m^2 for residential buildings and between 0.3 and 0.5 tons CO_2e/m^2 for office buildings.[1] The resolution of the data analyzed was only aggregated results extracted from literature. The study separated embodied from operational emissions, but there is no distinction between methodological choices and no separation between emission sources, building elements, and lifecycle phases. Thus, they were not able to do a thorough normalized comparison. Without such information, there is no way of knowing which building elements and which parts of the lifecycle these numbers represent, and hence if the results are reliable.

Large variation between building LCA studies is shown in another comparison of 116 cases from 47 scientific articles and reports [1]. Methodological issues and subjective choices of the LCA practitioner are found to cause huge variance in the results. The construction phase emissions vary between 0.03 and 2.00 tons CO_2e per m^2 gross floor area. The study concludes that "published building LCAs do not offer solid background information for policy-making without deep understanding of the premises of a certain study and good methodological knowledge".

Another meta-analysis of over 250 case studies from 70 papers mapped methodological aspects and found a need for clarity in methodological choices and a lack of uncertainty and sensitivity analyses. This study also called for more advanced LCA modeling such as including biogenic CO_2 dynamics, carbonation in concrete, and dynamic modeling to increase robustness and avoid false incentives [3].

1.4. Aims and objective of this study

To address the limitations discussed above, we present a novel method for estimating the lifecycle impacts on climate change imposed by material use in buildings over clearly specified THs.

The methodology builds upon previous research, including studies by the authors: structuring and storing inventory data [26], weighted average emission metrics for building subparts and including the effect of future technology improvements [25], using these to estimate average emission and material use profiles for building types [27], and a dynamic LCA of a cluster of buildings [28]. In this study, the methodologies are combined and developed further, additional methodological concepts are introduced, and the scope of emission sources is expanded along with the dataset.

We apply this method on primary inventory data acquired from 20 previously reported building LCA studies. Missing data in one building is imputed based on data from the remaining buildings, in this way

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[1] Converted to a functional unit of heated floor area over a 50 year lifetime, which was the lifetime used in most studies.

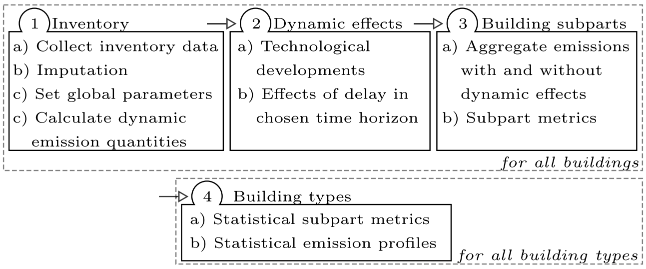

Fig. 1. Methodological steps.

ensuring more equal system boundaries of each study, thereby reducing underestimation of results due to incomplete system boundaries. This, together with the advantage of recalculating each study with equal model parameters, means that the given studies are harmonized bottom-up, for a more consistent statistical analysis. We perform this climate change impact analysis of the dataset based on building types, building elements, material categories, and emission sources.

The model's sensitivity to changes in methodological choices and parameters is thoroughly investigated, thereby determining which model choices and parameters are essential for obtaining high-quality LCA results that can be used to guide design choices and material-use policy.

2. Methods

This section first describes the goal and scope of the LCA 2.1 and methods for obtaining probability distributed dynamic inventory 2.2, future technology improvements and emission delay 2.3, biogenic carbon 2.4, and carbonation 2.6.

Then, descriptions of the methodological steps shown in Fig. 1 follow. Yearly emissions are first calculated for inventory items and *then* adjusted to the dynamic effects 2.7, which are then used to calculate emissions for building subparts, together with aggregated quantities and average emission-, technology-, and delay factors 2.8. These metrics are used to calculate statistical emission profiles of building types 2.9.

2.1. System definition

The goal of the analysis is to quantify the GWP_{TH} of an average square meter of heated floor area (HFA) in a building, over a given time horizon (TH), while also testing assumptions and methodological choices. The focus is on process-based, attributional LCA. The functional unit is m^2 of HFA over given building lifetimes and THs. In our dynamic interpretation of the GWP_{TH} impact, the accumulated radiative forcing impact of emissions occurring late in that period have less warming potential than emissions occurring early in the period, and the impacts of emissions occurring beyond the given TH are zero. Emissions are thus weighted by their time of occurrence to account for the accumulated effect on radiative forcing *during* that TH. Non-weighted emissions are also calculated for comparison; the effect of emission delay on the importance of future emissions is quantified in the *delay factors*, τ.

2.1.1. Scope of building elements

Fig. 2 shows the included building elements, structured according to the hierarchy classification in Norwegian standard NS 3451 'Table of building elements' [29]. The standard is widely used in the Norwegian construction sector to categorize building inventories, and consequently, also in building LCAs. Building elements available in at least one of the collected LCAs are included.

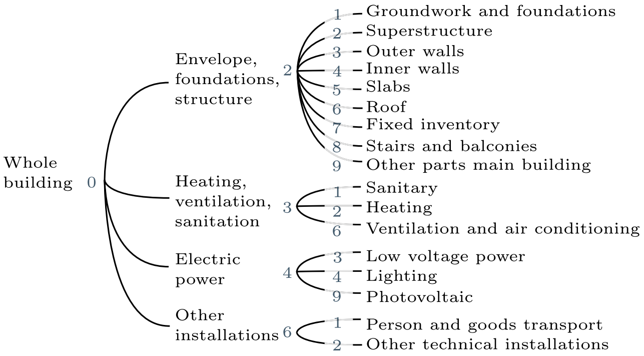

Fig. 2. Hierarchy classification of included building elements. Numbers, names, and hierarchy according to NS3445 [29].

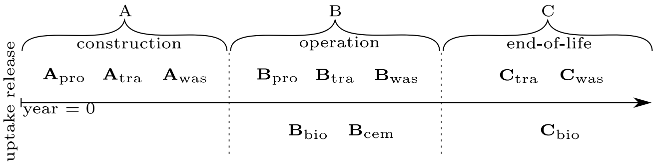

Fig. 3. Timeline of included emission sources and lifecycle phases.

2.1.2. Scope of emission sources

The study estimates material embodied emissions during the entire TH, i.e. the defined time of interest in the analysis (may differ from the building lifetime). The building lifecycle is separated into lifecycle modules as shown in Fig. 3: initial impacts from building construction in module A, impacts during operation throughout the building lifetime in module B, and end-of-life impacts in module C. In each temporal module, the model includes the emission sources material production (pro), material transport (tra), material waste (was), biogenic carbon uptake (bio), and carbonation of cement products (cem).

The widely used European standard EN 15978 separates modules into numbered submodules, e.g. A_{1-3} is cradle-to-gate material production. That module is here instead termed A_{pro}. This terminology is applied to all emission sources to ensure consistency and avoid ambiguity.

$\mathbf{A}_{\text{pro}}$ is the production of building materials, including construction waste. $\mathbf{B}_{\text{pro}}$ is the production of replacement building materials throughout the building lifetime, calculated as the statistically distributed $\mathbf{A}_{\text{pro}}$ emission for all replacement years.

Equivalently, $\mathbf{A}_{\text{tra}}$ is the transport of building materials and construction waste, and $\mathbf{B}_{\text{tra}}$ is the transport of replaced materials throughout the building lifetime, calculated as the statistically distributed $\mathbf{A}_{\text{tra}}$ emission for all replacement years. $\mathbf{C}_{\text{tra}}$ is the transport of all building materials to waste processing at the end of building life.

$\mathbf{A}_{\text{was}}$ is the oxidation of construction waste incinerated during initial construction. $\mathbf{B}_{\text{was}}$ is the oxidation of the replaced materials and construction waste of the new materials. $\mathbf{C}_{\text{was}}$ is the oxidation of the materials in the building at the end of building life. It is assumed that half of the carbon in the materials is oxidized by waste incineration and released into the atmosphere. The remaining half of waste materials could be either reused, recycled, or landfilled, however, related emissions are beyond the scope of the study.

$\mathbf{B}_{\text{bio}}$ and $\mathbf{C}_{\text{bio}}$ are the carbon sequestration from regrowth of trees due to use of biogenic materials in the building, both initial and replacement materials. The separation between the B- and C-phases depends on if the sequestration happens during the building service life (B) or after (C).

$\mathbf{B}_{\text{cem}}$ is the carbonation of concrete during the building's lifetime. Carbonation effects at end-of-life is not attributed to the building.

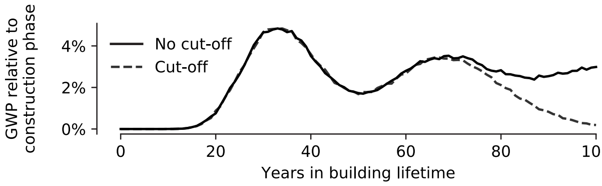

Fig. 4. Replacement emissions are chi-square distributed. Shows an example product with 35 years service life and 100 year building lifetime.

Table 1
Adjustments to future emissions. y=year in time horizon.

	Decay function	Half-life	Applies to
Technological progress			
Production	$e^{-.01y}$	69 years	B_{pro}
Waste	$e^{-.01y}$	69 years	B_{was}, C_{was}
Transport	$e^{-.02y}$	35 years	B_{tra}, C_{tra}
Production PV	$e^{-.037y}$	19 years	B_{pro}
Effects of delay			
T-year TH	$2 - e^{\frac{\ln(2)}{T}y}$	–	all
20-year TH	$2 - e^{.0347y}$	–	all
100-year TH	$2 - e^{.00693y}$	–	all
500-year TH	$2 - e^{.00139y}$	–	all

Climate change effects outside the study scope include the choice of building site, direct and indirect land-use change, albedo change, by-products of wood products (treetops, branches, roots, and chips), commute of construction workers and building users, energy use in operation, construction site (energy use and production of machinery, heating, temporary barracks, etc.), end-of-life substitution effects of reuse and recycling, and consequential LCA effects of choosing one product over another.

2.2. Probability distributed future emissions

The timing of future emissions relates to replacement times. The exact timing of a replacement is uncertain and uncertainty increases with time. To account for this, the years of future emissions can be represented by a random variable with increasing variance. This study uses the chi-square distribution, as shown in Fig. 4. The 'cut-off' assumes no replacements take place beyond the building lifetime. However, a sharp cut-off at the end of the building lifetime will not reflect that building lifetime is highly uncertain. The 'no cut-off' version, used in this study, acknowledges that building lifetime is an unknowable parameter by including parts of the emissions from replacements after the building lifetime. The effect of choosing other distributions is investigated in D.1 and found the 'no cut-off' chi-square distribution to transition smoothly as lifetimes change, and not underestimate, i.e. it includes the probability of early and late replacements.

2.3. Applying dynamic effects

Future climate change effects are adjusted by (1) expected technological progress, and by (2) their accumulated impact on climate change over a TH. Technological adjustments reduce emissions over future years, while emission delays reduce their *importance*. The calculation and effect on the results are equal for both adjustments: a lower climate change effect over the TH. Their effects on results are quantified as percentage reductions in total emissions by the tech factors ω and delay factors τ (see Section 2.8). The exponential e is often used to model natural decay when a quantity decays continuously by a fixed percent. Here, it is used to model both technological progress and the effect of delay by the functions shown in Table 1.

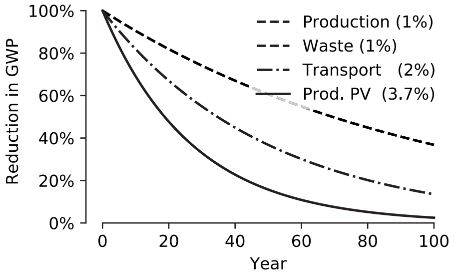

Fig. 5. Emission reductions due to technology improvements. Decay factors shown in parentheses.

2.3.1. Technological progress

Technological progress is implemented by weighing the probability distributed future emissions by exponential decay functions starting in the year of construction, see Table 1 and Fig. 5. With a ~1% yearly improvement for production of building materials, it takes 69 years for emissions to be cut in half. This improvement rate will in reality depend on material category, but distinguishing between types of materials will only have a noticeable effect on the results if the category makes up a significant share of the total. Faster development is applied to PV panels since they represent a large share, and historically, development has been steeper than average [30]. A ~ 1% development is also used for waste processing as reuse and recycling increases, and a lower share of combustible building waste is expected to be incinerated without carbon capture and storage (CCS) technology. For transport, the 2% decay factor cuts emissions in half in 35 years, due to efficiency gains and electrification. This implementation is a further development of a method by the authors [25].

The decay functions should not be interpreted as predictions, rather, they quantify the effect of *possible* development paths. The sensitivity of the decay factors was tested in the global sensitivity analysis, where each decay factor was varied between 0.5 and 4%. Results were sensitive to the decay factor of waste incineration, but not much to those of production and transport. Further description of these modeling choices can be found in B.1.

2.3.2. Delayed emissions

A GHG emission will heat the atmosphere as long as it is present, and its decay rate depends on the type of GHG. Hence, emissions that occur later in the TH have less time to trap heat in the atmosphere during that TH, and therefore have lower cumulative radiative forcing.

One way to calculate the cumulative radiative forcing over the TH (providing high accuracy and flexibility), is to integrate the Impulse Response Functions (IRF) of each GHG [4]. Without compromising accuracy, we here offer an approximated methodology. There are specific reasons for this simplification: Building LCAs often rely on EPD data, making it impossible to separate the different GHGs and therefore not possible to use IRFs; Simplification facilitates widespread application in research and the practice of building professionals; It is easy and computationally efficient to estimate results for a wide range of THs.

All LCA approaches rely on the choice of a TH, even if it is infinite or not explicitly stated [4]. For coherence, the delay of emissions must be considered for all emission sources [4,31]. Time-discounting with a TH of T years provides *the building's impact on climate change over the next T years*, thus being consistent with the physics of climate science.

An example TH of 100 years is plotted in Fig. 6. Weighting factors were first calculated with IRFs for every tenth year based on the method in [4], and the analytical function was fitted thereafter. It was found that an exponential decay function of $2 - e^{\frac{\ln 2}{100}y}$ fits the curve for a 100-year TH. Similar functions are used for other THs, where the decay factor for a TH of T years is $\ln 2/T$, making it easy to change TH. A detailed description including other THs can be found in B.2.

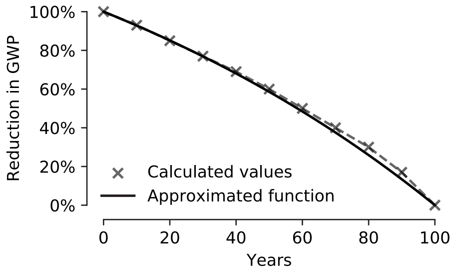

Fig. 6. Reduction in climate change impact due to delay in 100-year TH.

To test the accuracy of this simplified method, a calculation was performed for emissions of 1 kg CO_2e every year in a 100-year TH, with this method and with the original method [4] on which the simplification is based. The method proposed here achieves results that are only 0.2% off from an equivalent IRF calculation, making this accuracy fully acceptable compared to remaining model uncertainty.

2.4. Oxidation of stored carbon

Storing carbon in building products prevents release of that carbon to the atmosphere as long as it is in use. At the end-of-life stage, the stored carbon may be released in waste incineration, or stored further in other reuse and recycle products or landfills, and it may be subject to CCS technologies.

The carbon can be of biogenic or fossil origin. Although the biogenic carbon cycle is much shorter than that of fossil-based materials, the effect of carbon release from a building product to the atmosphere will be independent of its origin. All carbon stored in building products is therefore treated equally. The oxidation occurs far into the future, making both the timing and the fraction released into the atmosphere unknown. Therefore, timing is statistically distributed and we assumed that 50% of the stored carbon is released to the atmosphere at the end of the product life. Technological progress reduces the fraction released to the atmosphere by $\sim$ 1% annually. The LCA results were found to be highly sensitive to these two parameters in the global sensitivity analysis (GSA).

2.5. Biogenic carbon uptake

Biogenic carbon stored in harvested wood products contributes to climate mitigation by postponing its release to the atmosphere, while simultaneously leading to accelerated regrowth of new trees. Over time, this is a nearly carbon-neutral system, while fossil carbon permanently adds CO_2 to the atmosphere. The net effect of biogenic carbon (emissions minus uptake) can become negative when the effects of delaying and avoiding oxidation are considered. This is a benefit that fossil-based products do not have.

The wooden building materials are assumed to originate from sustainably managed forests kept under continuous rotation. Within the rotation period, i.e. the time of a full regrowth and trees ready for reharvest, the same amount of carbon will have been sequestered as was cut down. Carbon sequestration is attributed to the regrowth of the forest after harvest and not to the actual carbon stored in the building materials. Harvesting will not increase the carbon stored in the harvested trees, but it *will* increase the sequestration rate of the forest; it is this consequence we assess here. Alternatively, uptake can be considered to happen before harvest in the actual trees cut down, which would significantly affect results since no effect of emission delay would apply and no TH cut-off. The time distribution of the uptake of CO_2 over the years y in the rotation period is modeled by the first derivative of the Chapman–Richards (CR) growth function

$$f_{\mathrm{CR}}(y) = kpe^{-ky}(1-e^{-ky})^{p-1}, \tag{1}$$

where $k = 0.23$, $p = 3$ are model parameters describing the growth rate and catabolism of the trees. Eq. (1) is multiplied by the CO_2 content of the material and then normalized to account for an assumed rotation period of 100 years

$$f_{\mathrm{bio},\ i}(y) = m_{\mathrm{CO}_2,i} \cdot f_{\mathrm{CR}}(y) / \textstyle\sum_{y=0}^{100} f_{\mathrm{CR}}(y), \tag{2}$$

where $m_{\mathrm{CO}_2,i}$ is the mass of stored CO_2 in inventory product i. Fig. 7 shows emission profiles of biogenic uptake and release including replacements and the effect of delay. The regrowth profile will depend largely on the type of trees and climate, leading to different parametrizations of this function. The normalization reduces the importance of parameters k and p, leaving a 100-year rotation period the most sensitive parameter. The GSA found results to be highly sensitive to rotation period when equal to the THs but insensitive in shorter and longer THs. Further description and figures are presented in B.3.1.

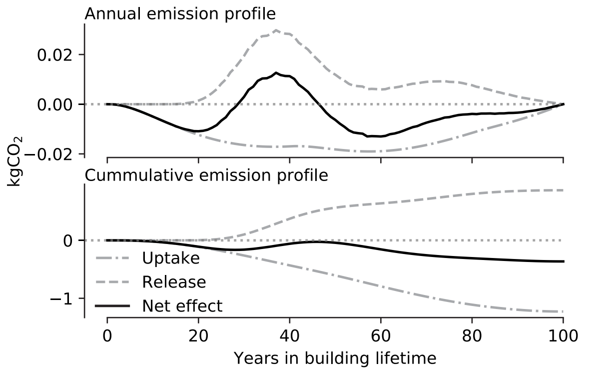

Fig. 7. Biogenic carbon uptake and release from 1 kg wood product and its replacements every 40 years. Effect of delay in a 100 year TH is considered. Construction waste omitted.

2.6. Carbonation of cement

Cement products will, over the building lifetime, bind carbon dioxide from the ambient air in a process called carbonation. Such a carbon sequestration mechanism gives negative emissions that may partly compensate for emissions from production of the materials. It is uncommon for building LCAs to consider carbonation in cement but some studies were briefly reviewed in [3]. The carbonation rate varies widely between cement-based products and between studies. The sequestration is lower for low-carbon concrete mixed with fly ash or slag. In general, the review found that the carbonation did not deeply affect the net emissions over the product's service life. When crushed and used as recycled aggregate in its next lifecycle, an uptake of ca. 20% of initial emissions can be sequestered. However, that uptake is not part of the product lifecycle and C_{cem} is therefore zero.

Without detailed data on each cement product in the inventory and their exposure to ambient air, it is not possible to accurately assess the carbonation of these products. Nevertheless, a general assumption of 0.1 $kgCO_2$ uptake per kg cement over 100 years was made. About half of the 100-year uptake happens the first 25 years, using an exponential decay function $1 - e^{-.03y}$ normalized for the years y in the building lifetime. This sequestration model was constructed based on information from [32]. Calculation details are given in B.3.2.

Carbonation is modeled for products in the material categories 'cement' and 'concrete'. The cement content in concrete varies, but a minimum of 400 kg/m^3 concrete is recommended [33]. For a concrete density of 2400 kg/m^3, this corresponds to a cement content of 17%, which is the assumed fraction in this study. The cement content was varied in the global sensitivity analysis from 10 to 23% (upper and lower values used in [33]) and was found to be one of the least sensitive parameters.

2.7. Calculation of building material emissions

Building material data is organized in a material inventory where each item is assigned to a building element and material category. For calculation, each inventory item must have a specified quantity q (per m^2 HFA), density ρ (if the unit of q is not kg), emission intensity per unit f, estimated lifetime of the material l, transport distance from factory d, and transport emission per weight and distance t. When any of these are not known for a given inventory item in one building they are estimated by approximation, using the existing data for similar inventory items in all case buildings. The methodology developed for imputation of missing data is described in A.4.

The imputed inventory data, together with the global study parameters (summarized in Fig. 13 and C.1), are used to calculate emissions as described above. Further calculation details are given in B.3. Each emission source is first calculated for every inventory item, for each year in the TH. To incorporate the dynamic effects, the yearly emissions for each inventory item are then adjusted by the technology and delay vectors.

2.8. Aggregation metrics for building subparts

The materials in a building are organized into building *subparts*. Subparts are building elements, material categories, or a combination of the two. The building elements are here organized in the hierarchical system in NS 3451 [29], shown in Fig. 2. The material categorization is based on the material groups described in C.2.

Both original and tech- and delay-adjusted inventory results are aggregated up to building subparts. From these aggregated subpart results, one can calculate average metrics that, for each subpart, describe the impact of each emission source and the magnitude of the dynamic effects.

For each subpart, the total mass is given by *quantity* Q, and the mass-weighted mean transport *distance* by D. The *emission factors* α, β, γ are the mass-weighted mean emission intensities, for the construction, operation, and end-of-life phases, respectively. The *tech factors* ω and *delay factors* τ are the emission-weighted average of the functions in Table 1 and Figs. 5 and 6, and describe how much future emissions (phases B and C) are reduced due to technological improvements and a subsequent effect of delay; these are calculated by division of the adjusted and unadjusted subpart results. Analytical equations for these metrics are given in B.5.

Emissions can be directly recalculated from these aggregation metrics; relationships between the metrics and emissions are shown in Table 2.

2.9. From buildings to building types

General characteristics of the case studies, such as location (climate, construction practice, etc.), typology (building form, special requirements, etc.), and type of superstructure (timber, concrete, etc.) influence material use and emissions. Statistical material use and emission profiles are therefore only representative for buildings of similar characteristics.

The case studies are here classified by such building types, for which statistics are calculated. The most general building type includes all buildings, which is used to analyze subpart emissions by building elements and by material categories. Another building type groups by typology. A third type groups buildings by their timber content; a total weight ratio of 1/4 or more biogenic materials is considered a timber building and a lower ratio a concrete building. The case studies are all from similar climate zones in Norway. Most are designed to reduce emissions from material use.

The average quantity and emission-, tech-, and delay-factors of the case buildings are used to calculate building type emissions with the equations in Table 2. The resulting emission and material intensity profiles can be used as reference values or benchmarks for buildings with similar characteristics.

2.10. Dataset of case buildings

The full inventories from 20 previously reported building LCA case studies were collected from sources in academia and industry, presented in Table A.1. None of the studies had a defined TH for the climate change impacts, neither did they consider technological progress (only for energy use in operation; some assumed improvements in production of PV panels). All studies used a 60 year building lifetime, which is much lower than the national empirical average, but often used in LCA studies. These methodological aspects and the ones explained in the sections above are harmonized in this study. Missing data are imputed based on the remaining dataset. A full description of the dataset and the preparation of it for use in this study is given in A.1–A.4.

2.11. Sensitivity analyses

A variance-based GSAs (Sobol analysis) is performed to determine the influence of changes in the global study parameters (see C.1) on the final emission results. The SALib Python library [34] is used for this calculation. Model results are first sampled and then analyzed. The output, for which the sensitivity is quantified, is the sum of all emission sources and years in the TH, for the entire inventory from all buildings in the dataset. It should be noted that the uncertainties of the inventory (LCI) data for the 20 case studies are not considered. The sampled results are also plotted and a confidence interval is calculated, providing an estimate for the uncertainty due to variation in the global study parameters.

The analysis is performed four times both for a varying TH and for fixed THs (20, 100, 500 years). This allows for a distinction between the uncertainty for each TH.

Table 2

Calculation of building subpart emissions [$kgCO_2e/m^2$] from aggregation metrics. The emission factors (α, β, γ) are without dynamic effects, which are adjusted for by the tech (ω) and time (τ) factors. Lifecycle phases and emission sources shown in parentheses, e.g A_{pro}.

	Const. (A)	Operation (B)	End-of-life (C)	Adjusted future (B+C)
Production (pro)	$Q\alpha_{pro}$	$Q\beta_{pro}$	–	$Q\beta_{pro}\omega_{pro}\tau_{pro}$
Transport (tra)	$Q\alpha_{tra}$	$Q\beta_{tra}$	$Q\gamma_{tra}$	$Q(\beta_{tra}+\gamma_{tra})\omega_{tra}\tau_{tra}$
Waste (was)	$Q\alpha_{was}$	$Q\beta_{was}$	$Q\gamma_{was}$	$Q(\beta_{was}+\gamma_{was})\omega_{was}\tau_{was}$
Biogenic uptake (bio)	–	$Q\beta_{bio}$	$Q\gamma_{bio}$	$Q(\beta_{bio}+\gamma_{bio})\tau_{bio}$
Cement uptake (cem)	–	$Q\beta_{cem}$	–	$Q\beta_{cem}\tau_{cem}$

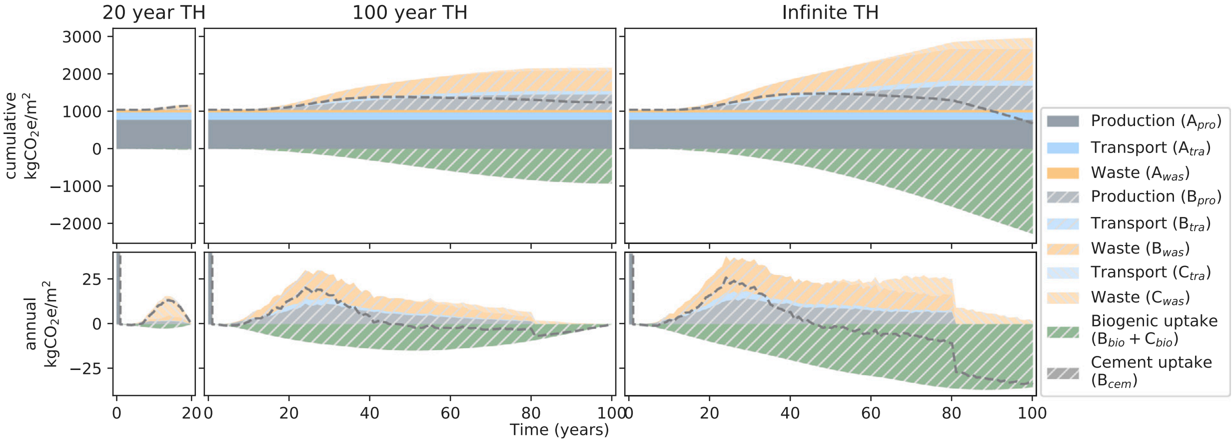

Fig. 8. Cumulative (top) and annual (bottom) climate change effect for different time horizons (TH). The stippled lines show the net climate change effect.

3. Results

3.1. Dynamic emission profiles

Fig. 8 shows the dynamic emission profiles of various THs, for a building with 80 years' lifetime. This building makes a good explanatory case due to significant future emissions. Results for the other buildings in the dataset can be found in E.4.2, many of which have much lower future impacts.

During a 20 year TH, the construction emissions are the only emissions that matter and the benefits of biogenic uptake are absent. If the goal is to minimize the climate change effect of the building within the next 20 years, one should focus solely on reducing construction phase emissions.

If the goal is to reduce the warming effect during the next 100 years, operation phase emissions become important for this particular building and benefits of biogenic uptake are highly present. The end-of-life phase will barely contribute to warming during those 100 years and should not be a priority.

With an infinite TH (equivalent to not including the effect of emission delay) all three phases are relevant. It is worth noting that for the infinite TH, the future emissions become highly uncertain, to the degree that these should preferably not be used to guide policy. It is highly uncertain and not meaningful to predict how the model parameters will develop over the next centuries. This uncertainty is greatly reduced in the 20 and 100-year THs, making them better suited for informing mitigation efforts.

3.2. Statistical emissions of building types and subparts

Figs. 9–12 show emissions for various building types and subparts with 80 year lifetimes and 100-year THs. Equivalent figures for other THs can be found in E. With a limited number of buildings, the material use, design characteristics, and study specifics of individual buildings will highly influence the emission profile. The building type and subpart emissions must, therefore, be interpreted together with the error bars showing the standard deviation (if sample size > 1).

Buildings with larger quantities of wood tend to have lower emissions, both due to biogenic carbon sequestration and lower emissions from material production, where wood products substitute the use of higher emission intensity products. The high waste emission factors (α_{was}, β_{was}, γ_{was}) for buildings and subparts with large quantities of wood products is compensated by high uptake factors (β_{bio}, γ_{bio}), especially in long THs. The carbonation factor (β_{cem}) is low compared to other emission factors; its mean value for all buildings lies within −13 and −8.5 gCO_2 per kg of all building materials in the buildings (95% confidence). Carbonation accounts for an average of $4 \pm 1\%$ (95% confidence) of total construction phase emissions for all buildings, given a 100-year lifetime and an infinite TH. Shorter lifetimes and finite THs reduce the importance.

The tech factors cause roughly a halving of future emissions (B- and C-phases), and the delay factors roughly another halving on top of that. Two effects explain the variation of tech factors among emission sources: technological development (Table 1) and timing of replacements. The variation in delay factors is explained solely by the timing of future emissions.

Fig. 9 shows metrics for each typology and emissions calculated from the metrics. The comparison is restricted to the buildings' envelope, foundation, and structure (building element 2) since this is the system boundary in most case studies. There is no clear correlation between higher emissions and their quantities and emission factors. The construction phase (A) dominates, while the future lifecycle phases operation (B) and end-of-life (C) are much less significant. The average net emissions in the construction phase are 402 ± 89 $kgCO_2e$, in the operation phase they are -54 ± 59 $kgCO_2e$, while the end-of-life phase is barely present at 9 ± 6 $kgCO_2e$ (95% confidence). The relative contributions of A, B, and C will, however, largely depend on the chosen TH and building lifetime. The construction phase is the same in all THs, but the equivalents for B and C are -4 ± 4 $kgCO_2e$ and 36 ± 17 $kgCO_2e$ in a 20-year TH, and -130 ± 100 $kgCO_2e$ and 284 ± 208 $kgCO_2e$ in a 500-year TH. The confidence intervals are expected to be smaller for a dataset with more case buildings of similar characteristics.

Fig. 10 shows metrics for timber and concrete building types and emissions calculated from the metrics. The comparison is restricted to building element 2. Although the timber buildings perform better on average, there is large variation within both building types. The timber content cannot alone explain this variation.

Figs. 11 and 12 explore building elements and material categories of all buildings. Fig. 11 shows metrics for each building element and emissions calculated from the metrics. The figure is split into three hierarchies, where the top hierarchy 0: 'Whole building' shows the results for all materials included in the system boundaries. The next hierarchy shows these same emissions split into building elements (one-digit), that are again split into more specific building elements (two-digit). The majority of emissions can be attributed to the main building structure (building element 2; corresponds to 'All buildings' in Fig. 9). 'Electric power' is also responsible for a significant proportion due to photovoltaic panels on some buildings.

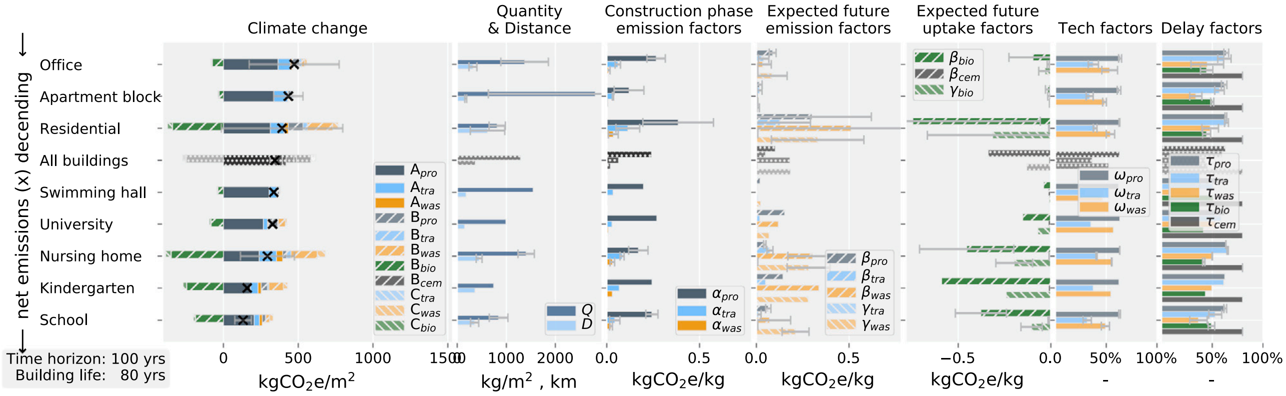

Fig. 9. Emissions and average metrics for building types; building element 2. Average building type metrics used to calculate emissions. Standard deviation shown in error bars.

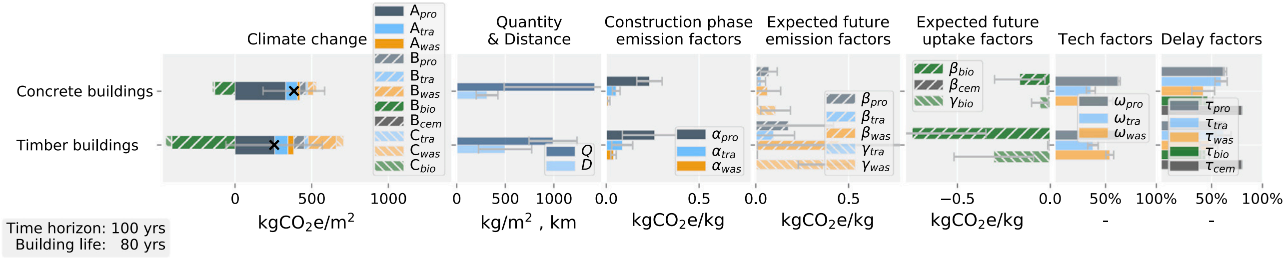

Fig. 10. Emissions and average metrics for timber (>1/4 biomaterials by weight) and concrete building types (≤ 1/4 biomaterials); building element 2. Average building type metrics used to calculate emissions. Standard deviation shown in error bars.

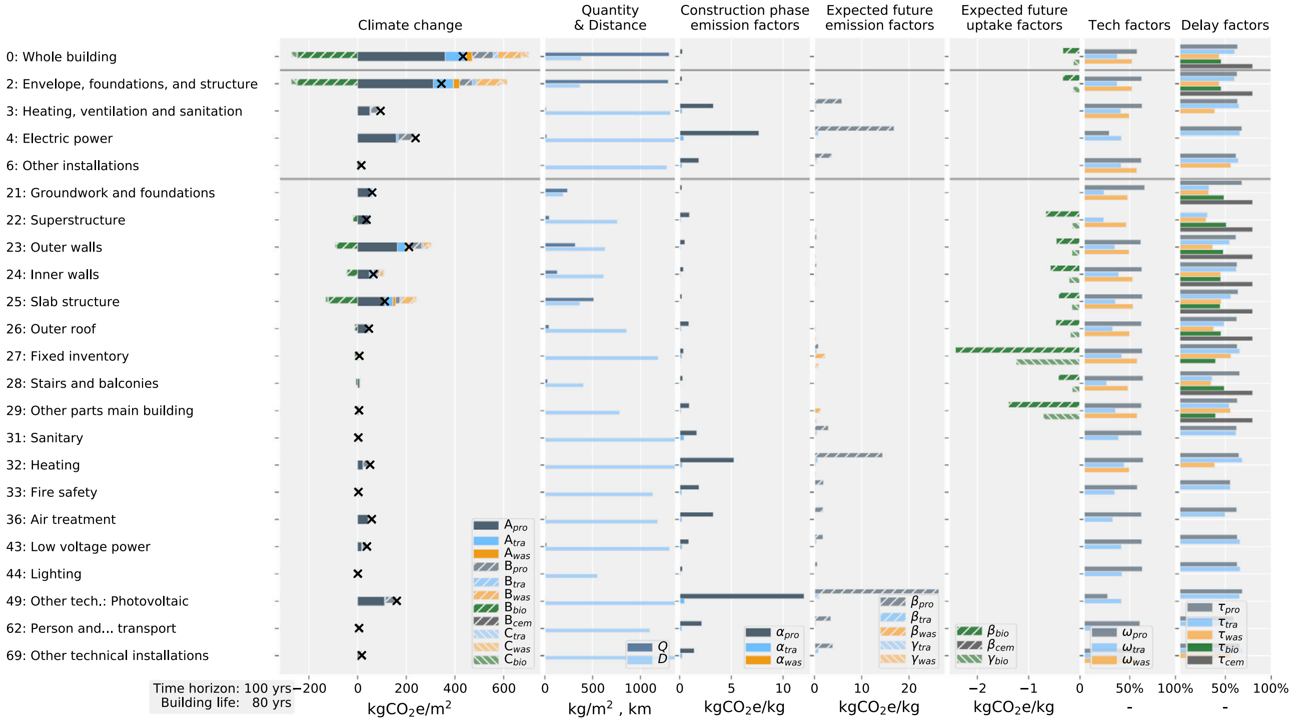

Fig. 11. Emissions and average metrics for building elements; all buildings; all building elements where data exists. Horizontal lines divide the three hierarchies. Average building type metrics used to calculate emissions. Standard deviation shown in error bars.

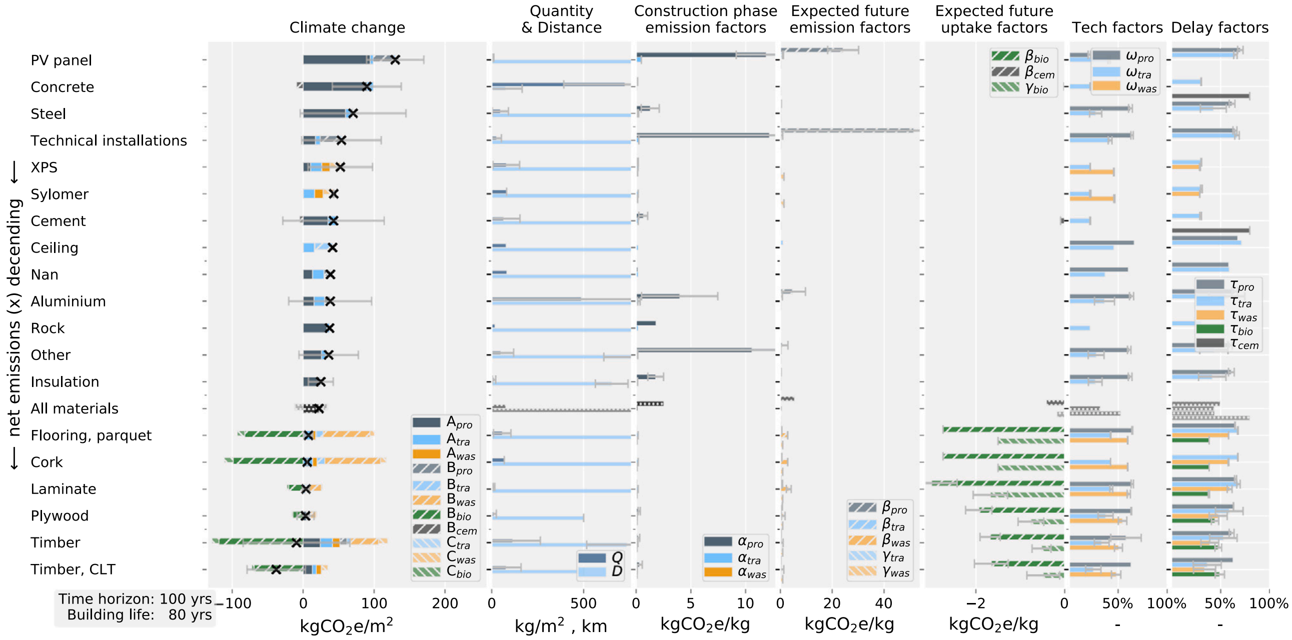

Fig. 12. Average emissions of material categories in all buildings (not calculated from metrics). Material categories with low contribution (positive and negative) omitted. Standard deviation shown in error bars.

Fig. 12 shows the average emissions of each material category (not calculated from metrics). Material categories contributing little to total building emissions are excluded from the figure.[2] Of the remaining material categories, the ones with biogenic carbon have the lowest average contribution to building emissions. Emissions vary widely within most material categories, seen as standard deviation in the error bars. Based on the material use in the case buildings, both promising material categories for reduced climate change and culprits can be identified. However, the material categories must be evaluated together with their structural, functional, thermal, and aesthetic properties.

3.3. Sensitivity of methodological choices

Fig. 13 shows the distributions of sampled results and the resulting total sensitivity indices of the global parameters. The assumption is uniform distributions within the parameter ranges shown in the figure. Only sensitivities of the global study parameters are investigated, not those of the underlying material inventory data.

Parameter sensitivities highly depend on the TH, which is a normative choice. GSAs are therefore performed for varying (20–500 years) as well as fixed (20, 100, 500 years) THs. When TH is allowed to vary together with the parameters, it is by far the most sensitive model parameter and is responsible for 61 ± 10% (95% confidence) of the model variance, followed by building lifetime at 16 ± 3% (95% confidence). The remaining sensitivities relate mainly to the end-of-life incineration of construction waste and biogenic carbon sequestration. The sampled results vary widely, between −0.3 and +0.5 tons CO_2e/m^2 (95% confidence). Thus, climate change impact cannot be determined with any meaningful accuracy without specifying TH; results are not very useful for policy if the sensitive parameters are not precisely known.

For shorter THs, however, results become much more precise. With the assumption of an accurate material inventory, 95% of results are between 0.39 and 0.53 tons CO_2e/m^2 in a 20-year TH, and between 0.20 and 0.50 tons CO_2e/m^2 in a 100-year TH. In the 500-year TH, the variation is on scale with the GSA where TH varies. Thus, shorter THs yield more precise results, while long THs (i.e. predicting impacts far into the future) are highly uncertain. Parameter sensitivities change in short THs: building lifetime is not relevant for THs around 100 years or shorter. The rotation period is highly sensitive for the 100-year, but not for other THs.

Independent of TH, carbon content of bioproducts, fraction incinerated, and waste fraction are always highly sensitive. This calls for refining both the modeling of these effects and the data inputs used, to reduce these uncertainties. For policy, it suggests that limiting construction waste and increasing reuse, recycling, and CCS should be high priorities.

Values of sensitive parameters should be chosen with care. Uncertainties of insensitive parameters do not affect the model output much, hence, it is less important that these are precise. The TH should be a deliberate normative model choice defining the temporal scope of the research question. For the remaining sensitive parameters, more precise estimates can be obtained empirically, which will reduce their sensitivities.

Choice of statistical distribution for future events is explored in D.1: The chi-square distribution and normal distribution with time-dependent variance are found most fit. Integer numbers of replacements should be avoided since they will lead to abrupt changes in results when material and building lifetimes change, and fractional numbers will underestimate replacement emissions. The importance of choosing an appropriate distribution is especially important if dynamic effects are not considered or under long THs.

Choice of TH is further explored in D.2: The A-phase is independent of TH. Longer THs lead to higher emissions from the B-phase. The importance of the C-phase increases for THs longer than building lifetime.

Choice of building lifetime is further explored in D.3: In general, shorter lifetimes lead to lower impact from the B-phase and higher impacts from the C-phase. The A-phase is independent of building lifetime, while the B- and C-phases greatly depend on it in long THs.

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[2] The excluded categories contribute less than 10% of the maximum absolute sum of positive and negative emissions, and are 'Acoustic insulation' 'Asphalt' 'Bitumen roofing' 'Brick' 'Carpet' 'Coating' 'Copper' 'Doors' 'EPS' 'Elevator' 'Flooring' 'Flooring, ceramic tiles' 'Flooring, tiles' 'Glass' 'Glass wool' 'Granite' 'Gravel' 'Gypsum' 'Gypsum, plaster' 'Heat pump' 'Hot water tank' 'Insulation, mineral' 'Linoleum' 'Membrane' 'Paint' 'Plastics' 'Rubber' 'ST collector' 'Sink' 'Timber, Gluelam' 'Vinyl' 'Windows' 'Wood wool'.

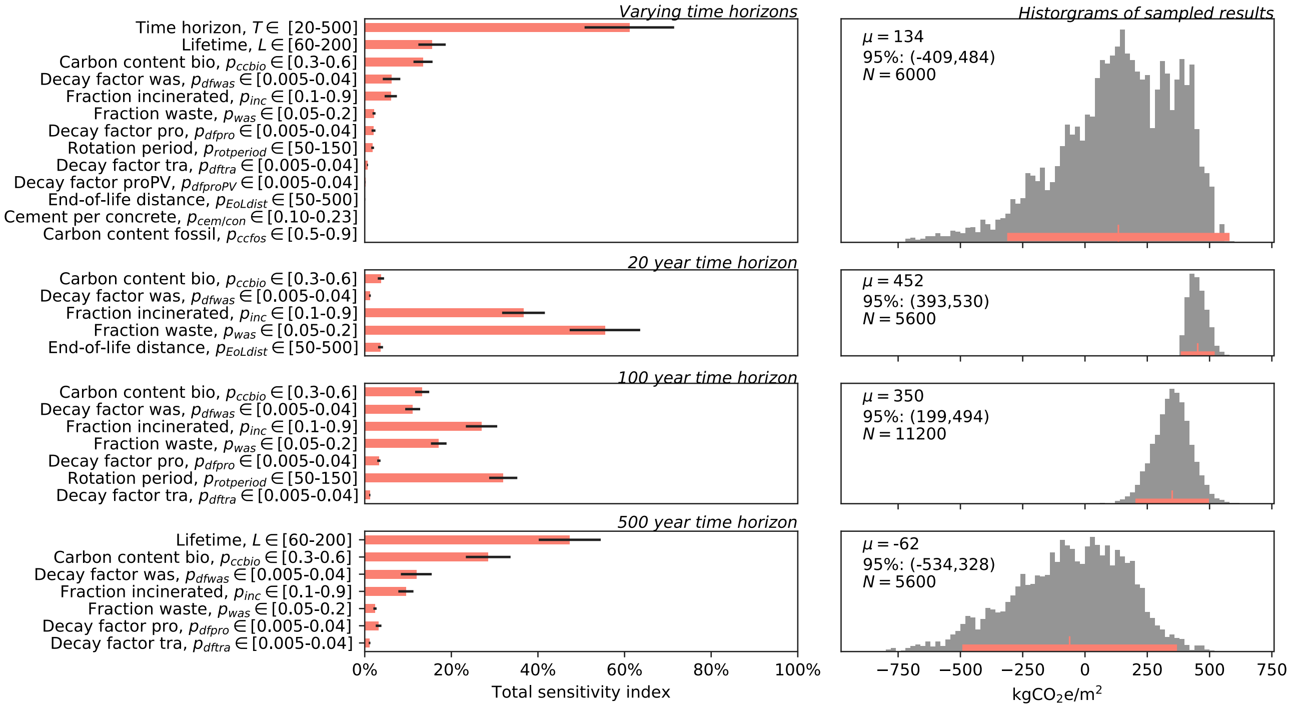

Fig. 13. Relative sensitivity of the global study parameters for various THs (left) calculated from sampled model results (right). The black lines (left) are 95% confidence intervals of the sensitivity indices. The orange bar (right) shows the mean μ and 95% confidence interval of the N sampled results. For the 20, 100, and 500-year THs, parameters that contribute less than 1% are not shown.

Building lifetime is an unknowable parameter, and under long THs it contributes to large uncertainty in the results of the future lifecycle phases, while its contribution to uncertainty is greatly reduced with shorter THs.

4. Discussion

4.1. Acknowledging uncertainty

In the complex system of processes related to a building and the quantification of impacts many decades into the future, there are great uncertainties that one should be aware of. First, the inventory data must be accurate for its intended purpose, which again must match the purpose of the assessment. This is not always the case for emission intensity data, inventory quantity data, etc. Secondly, both the timing and the nature of several future events cannot be known with any certainty. This should be reflected in the implementation of the dynamic effects, which is here modeled without adding superfluous complexity. This makes the method transparent, understandable, and open to scrutiny while reducing the chance of errors.

A major advantage of the method offered in this study is that the temporal assessment of dynamic effects reduces model uncertainty. Future technological progress is uncertain, indeed, but the assumption of *some* development is better than *none*; including the phenomena of technological progress improves on previous methods. The inconsistency of products with different THs is resolved by accounting for delayed emissions. An additional benefit of factoring in the timing of emissions is that the discounting is inversely proportional to the uncertainty due to time. The further into the future, the larger are the uncertainties, however, these increasing uncertainties will be offset by weighting emissions by their distance into the future. Technological development has the same uncertainty-reducing property. Additionally, results are less sensitive to uncertain parameters such as building lifetime. By significantly reducing the uncertainty of postulated future impacts, this is an important step in the direction of more policy-relevant modeling. The shorter the TH, the more the results can be trusted.

Imputation of missing data involves uncertainties. Nevertheless, a sufficiently good imputation strategy enables use of more data in the analysis, contrary to excluding that data and accepting underestimation and weaker analyses. The imputation strategy is based on the expected value of similar materials, implying that the larger the dataset the better the strategy will work.

A GSA should be performed for all complex models, especially for models used to guide policy [8]. The GSA ranks the model's sensitivity to changes in parameters. Parameters with high sensitivity indices are contributing highly to model uncertainty, and are therefore important to assume accurately. It is less important to have precise values for the parameters with low sensitivity indices because a change in these will not change the results much. Additionally, sensitivity was explored by testing the effect of model assumptions.

4.2. Harmonization of data and assumptions

This study has a unique advantage over previous statistical studies in literature, since the complete inventory of each building makes it possible to redefine the system parameters and test assumptions. This allows for a deep harmonization of assumptions and parameters among all case buildings. Furthermore, data uncertainties can be mitigated by statistical power and the representativeness of results improves as the dataset grows. Results are representative only of the range of typologies addressed and Norwegian conditions. The method, however, can be applied to any typologies and geographic conditions.

4.3. Delayed emissions

When using GWP (CO$_2$ equivalents) for emissions that occur far into the future, it is methodologically and policy-wise inconsistent not to assess impacts by use of a dynamic framework. A TH is included by default in the GWP indicator (usually 100 years) and to later ignore this TH in the LCIA is inconsistent. If there are significant quantities of GHGs other than CO$_2$ this could invalidate those results. The importance of this inconsistency will, however, be small in cases where CO$_2$ is the dominant GHG.

Building LCAs often collect climate change data for building materials from EPDs, where single-valued results make time-profile distinction between the GHGs impossible. The dynamic time horizon method presented in this paper can be used even for such aggregated CO_2e emission intensities. A problem remains: the climate change impacts of inventory data in this study are GWP_{100}, thus, the application and results will only be completely consistent for the 100-year TH. Other THs will always be consistent for CO_2 emissions, but not for the share of CO_2e linked to other GHGs. This is a limitation that may be acceptable considering the applicability of the proposition, especially in cases where CO_2 is the dominant GHG. The limitation can be resolved by matching the TH of the GWP of the inventory with the TH used to account for delayed emissions.

The use of a consistent TH not only ensures methodological quality and reduces uncertainty, it also answers a research question much more relevant for policy than does an infinite TH; namely '*What will be the cumulative impact over the TH, of choices made today?*' in contrast to the impossible question of what will happen in the unforeseeable future.

4.4. Subpart metrics

The quantity, distance, emission-, tech-, and delay factors are weighted average values of the inventory items in the subpart, describing the subpart's environmental performance. In this paper, the metrics are used for generating statistical emission profiles of building types. Additionally, these metrics are relevant for the interpretation of results, as design drivers, and for benchmarking and verifying LCA calculations. Another use is as proxy values in early-phase planning and for emission sources and building elements outside the study scope. Furthermore, non-dynamic building LCA results can be adjusted for technology and delay effects by multiplication with the tech and delay factors.

4.5. Limitations

There are some limitations that the reader should be aware of. Climate change effects outside the study scope are listed in the Methods section; this study focuses on material use in buildings. Emission sources such as energy use at the construction site and during operation are also highly important to consider.

This study uses process-based attributional LCA. Input–Output, Hybrid, and Consequential LCA are more relevant for answering certain research questions and are compatible with the presented methodology.

A specific indicator is used; dynamic GWP within a TH. Other aspects of the climate system such as feedback mechanisms, temporal impacts to radiative forcing and temperature changes are not targeted, and results can change when using other indicators.

The GSA results in this study depend upon the inventory; an inventory with different material composition would result in other sampled distributions and parameter sensitivities. In further work, the GSA should incorporate the variability of the material inventory, additional variables, mathematical relationships, and boundary conditions for a complete assessment of sensitivity. The GSA results also depend heavily on the uncertainty ranges of the parameters given in its input; further work should revise the ranges empirically.

The carbon content of timber products is a highly sensitive parameter and should in future studies be determined individually for each inventory item where possible, instead of assuming a fixed percent for all wood products.

Results are only representative for buildings of similar characteristics and are biased by the case-specific conditions and designs of these buildings. The case studies are designed and constructed according to Norwegian practice for Norwegian climate and designed for low lifecycle emissions. This limitation does not hinder the applicability of the proposed method, just the extrapolation of numerical results.

The proposed solution to account for delayed emissions provides an estimate of the total radiative forcing during any chosen TH, in units of CO_2 equivalents. Thus, GHGs other that CO_2 must first be converted to that unit. As discussed in 4.3, the method is accurate for any TH *as long as the GWP of the inventory uses the same TH*. When the TH of the inventory is different from the TH of the study, calculations will be correct for CO_2 emissions, however, inaccuracies will arise for the share of CO_2e representing GHGs other than CO_2. One should therefore consider if the share of non-CO_2 GHGs is significant, and in that case adjust the inventory to the respective TH or else be aware of this limitation.

For systems of radical uncertainty, i.e. unknowable uncertainty, as defined by [35], qualitative judgments are needed. Not all types of uncertainties and not all problems can be quantified. Building LCAs over large periods involve radical uncertainties that should be investigated further.

4.6. Implications for building LCA practice

Dynamic effects are obviously important in building LCAs. Technological progress is very likely to happen during the coming decades and should no longer be ignored in modeling. Time horizons of warming effects should also be clearly defined, where the chosen TH should reflect the goal of the LCA. Future events should be represented by random variables with time-dependent variance. Model choices and parameters should be conveyed and their global sensitivities should be assessed.

Biogenic carbon sequestration and end-of-life incineration of stored carbon in building products have important effects on climate change that should always be included, especially for long THs. Carbonation of cement products seems to play a minor role during the use phase and may be ignored.

This paper presents a simplification of the DLCA method [4] for including effects of delayed emissions, which can facilitate its implementation into building LCA practice. It works for any TH and enables application with emission intensities from EDPs. This simplification preserves the underlying assumptions and adheres to the physics of climate change. Previous research has argued that dynamic approaches need to be simple to allow wider use both by academics and practitioners, and that methodological developments should aim at striking a balance between improving accuracy and limiting additional complexity [20]. This paper presented a simple method that does not compromise accuracy. LCA software should adopt the best available scientific methodology and not vice versa.

4.7. Implications for policy

The proposed method increases policy-relevance. As a consequence of future technology improvements, reduced climate change effect of delayed emissions, and less uncertainty, reduction of near-future emissions should be prioritized over distant future emissions. Encouraging the active choice of a TH forces policymakers to make an important choice regarding the rate of mitigation efforts.

Even with equal assumptions and methodology, the differences in material inventories of the 20 case buildings lead to large differences in results, but despite the variation, there are some trends. Mitigation of carbon embodied in material use should focus on the emissions happening in the construction phase, while emissions in the operation and end-of-life phases are much less important and much more uncertain. Buildings dominated by wood products have lower impacts, especially over long THs. Among the building elements included in the examined case studies, emissions from outer walls, slabs, and PV are dominating. Among the material categories, priority for low-emission products or alternative materials should be on PV panel, concrete, and steel, to mention some. Biomaterials can have climate mitigation effects and are promising alternatives.

5. Conclusions

A building can operate for centuries and this long lifetime introduces time-dependent effects that dynamic LCA can account for: technological progress will lead to lower future emission intensities; postponed emissions have lower warming potentials over a given TH; carbon stored temporarily in building products and the timing of its future oxidation can have mitigation benefits; carbon sequestration happens both in regrowth of trees and in building products containing cement. These effects are usually ignored in LCA studies of buildings. This paper proposed a robust methodology for, first, creating a dynamic inventory, and then, including these effects for any chosen TH.

The IPCC urges nations to rapidly reduce emissions to stay below the global temperature increase targets. The timing of emissions has implications for the climate change effect over the TH, and to limit the warming effect of human activities within the next 20 to 100 years, these effects can no longer be ignored. Overall, the temporal dimension is key to climate mitigation in the building sector. We show that a dynamic TH of T years can be modeled by multiplying dynamic emissions with the simplified function $2 - e^{\frac{\ln 2}{T} y}$ for each year y in the TH. This simplification can potentially make emission delay a default component of building LCA practice.

Future events that are highly uncertain should not be depicted as equally accurate as near-future events. The introduction of technology improvements and delayed emissions greatly reduces uncertainty related to future events. Decisive parameters such as the building lifetime also have less influence on the results, and thus on the conclusions and implications for policy. We regard this as an important step in the direction of more policy-relevant modeling.

The method was applied on the material inventory dataset of 20 case buildings, harmonized to get a more consistent comparison and statistical treatment. The main focus of embodied carbon mitigation efforts should be on the near-future construction phase impacts since these dominate the lifecycle emission profile and can be more immediately influenced in building design as well as by policy. Reducing emissions from waste incineration also has significant mitigation potential. Limiting construction waste and increasing reuse, recycling, and CCS should be high priorities. The use of wood products in buildings can have mitigation effects, mostly over long THs. Carbon uptake in cement products is only a fraction of construction phase emissions; hence, choosing alternative materials or low-carbon concrete is outweighing the effect of carbonation. Future technology improvements may lead to a rough halving of future emissions, and emission delay leads to another halving of their climate change effect the next 100 years, making these dynamic effects responsible for about a 3/4 reduction of future emissions.

Emission results vary widely depending on parameter choices, with time horizon, building lifetime (long TH only), and waste related parameters responsible for most of the model uncertainty. The differences in material inventories of the 20 case buildings also lead to large differences in results. Statistical inference can be improved by applying the demonstrated modeling approaches to a larger dataset of building case studies.

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.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.buildenv.2020.107399.

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Supplementary Materials to
Estimating dynamic climate change effects of material use in buildings—Timing, uncertainty, and emission sources

This is the supplementary material to
E. Resch, I. Andresen, F. Cherubini, H. Brattebø, Estimating dynamic climate change effects of material use in buildings–Timing, uncertainty, and emission sources, Building and Environment (2020) 107399
which can be freely accessed on
`https://doi.org/10.1016/j.buildenv.2020.107399`.

The main paper [1] presents a calculation method for quantifying the lifecycle climate change impacts of material use in buildings within defined time horizons, and applies the method on a dataset of collected building LCAs with a presentation of statistical results. Here, methodological concepts are explained in more detail, and additional results are appended. Each section is standalone and can be read independently of the others.

The dataset and its preparation and handling of missing data is described in A. The calculation methods are detailed in B and modeling choices in C. In D, the sensitivity of the model is thoroughly investigated. Additional important results, that did not fit into the main paper, are appended in E.

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A The dataset

A.1 Dataset description

The complete material inventory of 20 building LCA case studies was collected from various actors in academia and industry. Table A.1 shows the building LCAs that are included in the dataset used this study.

Table A.1: The building LCAs that are included in this study. #: number of alternative designs.

Name	#	Typology	Construction	Location	HFA [m^2]	Year, study
Papirbredden II	1	office	concrete	Drammen, Norway	8536	2012
ZEB SFH Concept	1	residential	concrete	n/a, Norway	160	2013
ZEB Office Concept	1	office	concrete	n/a, Norway	1980	2013
ZEB Living lab	1	residential	timber	Trondheim, Norway	102	2014
ZEB Multikomfort	1	residential	concrete	Larvik, Norway	202	2014
A14 Bjørvika	1	office	concrete	Oslo, Norway	4291	2014
Råstølen sykehjem	4	nursing home	2timber/2concrete	Bergen, Norway	8076	2014
NTNU Gjøvik	1	higher educ.	concrete	Gjøvik, Norway	5052	2016
Østensjø skole	1	school	concrete	Oslo, Norway	3629	2017
Prinsdal skole	1	school	timber	Oslo, Norway	1215	2017
Powerhouse Telemark	1	office	concrete	Porsgrunn, Norway	7908	2017
Flesberg skole	1	school w/sports hall	concrete	Flesberg, Norway	6664	2018
Flesberg sv.hall.	1	swimming hall	concrete	Flesberg, Norway	2344	2018
Eufemia B7 Vestbygg	1	apartment block	concrete	Oslo, Norway	8330	2018
Ydalir kindergarten	1	kindergarten	timber	Elverum, Norway	2140	2019
Ydalir school	1	school	timber	Elverum, Norway	6474	2019
Eufemia B7 Sørbygg	1	apartment block	concrete	Oslo, Norway	5616	2019

All buildings were designed for low lifecycle emissions related to both operational energy use and emissions embodied in building materials, they are all designed for Norwegian climate, and energy for heating is provided from electricity, sometimes with heat pump, and district heating. As is the case with any such statistical analysis it is worth noting that, due to a limited dataset, the results are biased by the case-specific conditions and designs of these buildings, as well as by the possibility of methodological differences in the original studies.

A.2 Dataset preparation

To account for methodological differences in the original studies, the primary inventory data (almost 2000 inventory items covering > 500 building material LCA data) for each study was manually controlled and systematized before it was imported into a further developed version of the building LCA database described by Resch and Andresen in [2]. In this database, the studies are made comparable by systematically organizing the original data used in the studies. Material inventory of the buildings and other relevant information is stored in a SQL database that categorizes the inventory according to hierarchical building elements from the Norwegian standard NS 3451 Table of Building Elements [3], and according to material categories by predefined material and product groups.

A.3 Missing data and completeness of data

All the collected cases are to various degrees missing data necessary for performing the complete calculations in the same manner for all cases. Missing information can be due to deliberate differences in study scope (i.e. the system boundary of building elements and lifecycle phases, or only including major product groups), or it can be due to study limitations leading to inaccuracies within the study scope. Missing data thus occurs in *inventory item specification*, in *completeness of system boundary*, and in *completeness of inventory items* within the system boundary. This section describes how such missing data is handled.

If data is missing in the inventory item specification, i.e. the quantity, density, emission intensity, lifetime, transport distance, or transport emission intensity is missing, then that data is imputed by a methodology specifically developed for this study. Data from the remaining studies is used as proxy for the missing values. The imputation strategy is explained in A.4.

Studies with limited system boundaries are missing entire building elements or lifecycle phases. These missing parts are not a problem in statistical results as long as at least one study has the data, since other case studies that have those parts included will be used for calculation of those building elements or lifecycle phases.

Missing inventory within the system boundary is more problematic. If studies are missing materials within the inventories of building elements or material categories, it is impossible to detect it directly. Such cases are likely common, since all inventories are at the very least missing non-influential details such as screws, and possibly also more influential building materials. Each study is somewhere on the continuum of including only major material groups and including every single material. Missing inventory can therefore be an important source of variation between studies, and should be controlled for in future studies. It is likely that the results from all studies are to some degree underestimated.

A.4 Imputation of missing data

In the inventory items of the entire dataset, denisty ρ, material lifetime l, transport distance d, and transport emission intensity t are missing in 52%, 37%, 78% and 78% of the in total 1860 inventory items, respectively. These are all estimated and imputed based on the remaining inventory in that building and in all other buildings. The strategy of imputation depends on the feature.

The material density, ρ [kg/FU], is imputed based on the mean of all materials with the same functional unit (FU) in the same material category. If that doesn't exist, it is imputed based on the mean of all materials of that functional unit.

The material lifetime, l [years], is imputed based on the mean lifetime of materials of the same material category used within the same building element. If there is no lifetime value for materials from that building element, the building element one step up in the hierarchy of building elements is attempted next, and then another step up after that. If that doesn't exist either, it is imputed based on the mean of all materials within the same material category. It there are no lifetime values for the material category it is imputed based on the mean of all materials in the dataset.

The transport distance from the factory to the building site d [km] is imputed based on the mean of all materials from the same material category. If that doesn't exist, the mean of all materials is used.

The transport emission intensity per weight and distance t is imputed with a fixed value from the Ecoinvent database ('Transport, lorry 16-32t, EURO5'), at .000166 [kgCO$_2$e/kgkm].

B The calculation

B.1 Technology adjustments

Technological improvements have, historically, led to significant reductions in energy intensity at country level and for the production of construction materials, and is one of the primary strategies for limiting the impacts of climate change. Historical trends of energy intensity reductions often follow exponential decay functions [4], which are here model as

$$e^{-ky}, \tag{1}$$

where k is the decay factor and y are the future years. The decay factor is a constant that determines the yearly rate of reduction. The future emissions are obtained by multiplying emissions at current emission intensity levels by Eq. (1) to adjust for future improvements in technology. It is not possible to predict with certainty how this development will continue in the future, but historical trends can be used as proxies to set the decay factors. A distinction is made between technological improvements in the areas of material production, transport of materials, waste processing, and electricity production. For material production, a further distinction is made between PV panels and the remaining building products. Figure B.1 shows the decay functions used in the study.

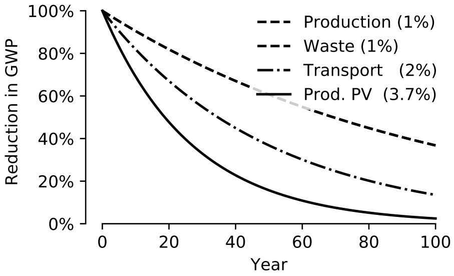

Figure B.1: Technology improvements; emission reductions relative to year zero. The percentages in parentheses are the decay rates of the exponential decay functions.

Historical data shows that the average annual improvements for the energy intensity for the production of the some of the most energy intensive construction materials (pig iron and aluminium) have been in the range 1.0–1.5% [4]. The use of recycled secondary materials, and substitution of materials with less energy intensive ones have potential for further reductions [4]. A decay factor of 1% is used in this study.

There will, of course, be variation between material categories. A particularly intensive material category is photo-voltaic (PV) panels, which has shown a steeper historical trend [5]. Here, a 2/3 reduction is assumed over a 30 year period (a standard lifetime assumption for PV panels), which results in a decay factor of about 3.7%.

Changes in energy intensity of countries (between 1995 and 2007) were mostly due to technological change while structural change was less important. For some countries, however, a structural change in the industry mix was the main reason for energy intensity reduction [6]. A more recent study shows that, when adjusting for international trade, the general global pattern is that the main force of increasing energy efficiency is technological progress [7]. Aggregate energy efficiency improved mostly due to technological change [6]. Technological advances thus seem to play the largest role in the energy intensity trends [7].

The global sensitivity analysis of the global study parameters shows that, with a range from 0.5% to 4%, only the decay factor for waste has significant influence on the study results. The decay factors for production and transport are less relevant. It is therefore most important that the decay factor for waste is accurate.

B.2 Temporal delay adjustments

A time-discounting with a time horizon (TH) of T years gives *the building's impact on global warming over the next T years* while adhering to the physics of climate science. The choice of TH is a normative one, which depends on the purpose of the assessment. How many years of future warming are important to the choices made today? Should the warming be limited within 2050, this century, or the next millennia? Which choices that should be made today will depend on the answers to those questions.

An example TH of 100 years is plotted in Figure B.2. Weighting factors were first calculated for every tenth year based on the method in [8], and the analytical function was fitted thereafter. An exponential decay factor of $\ln 2/100$ was found to fit the curve for a 100 year time horizon. Similar functions are used for other time horizons, where the decay factor for a time horizon of T years is $\frac{ln2}{T}$, making the method elegant and easy to apply.

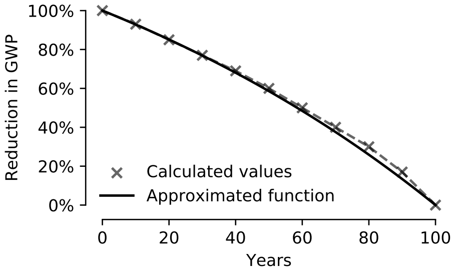

Figure B.2: Time-discounting. Relative reduction due to delay. Effect of delayed emissions with 100 year TH.

The temporal adjustment in year t for a time horizon of T years is

$$2 - e^{\frac{ln2}{T}t}. \tag{2}$$

Figure B.3 shows the decay constants $\frac{ln2}{T}$ for time horizons from 20 to 500 years. The maximum value that the exponent (the product of the decay constant and the time horizon) can take is a constant whos value is $\frac{ln2}{T}T = \ln 2 \approx .69$, independent of the time horizon. Figure B.4 shows the temporal adjustment vectors resulting from those decay factors applied in eq. (2), i.e. it shows the temporal adjustment vectors for different time horizons.

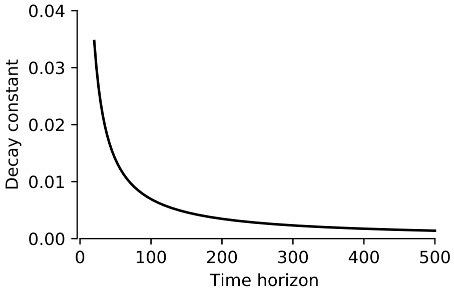

Figure B.3: Decay factors of the exponential in eq. (2), determining the rate of decay in the period up until the last year of the TH.

Such a simplification of the methodology must, of course, not significantly impact the accuracy of the results. To test accuracy, a calculation was performed for an emission of 1 kg CO_2e every year in a 100 year TH both with this method and with the original method from Ref. [8] on which the simplification is based. The method proposed here achieves results that are only a factor of two-thousandth off from an equivalent IRF calculation with the original method, making this imprecision irrelevant compared to the remaining model uncertainties.

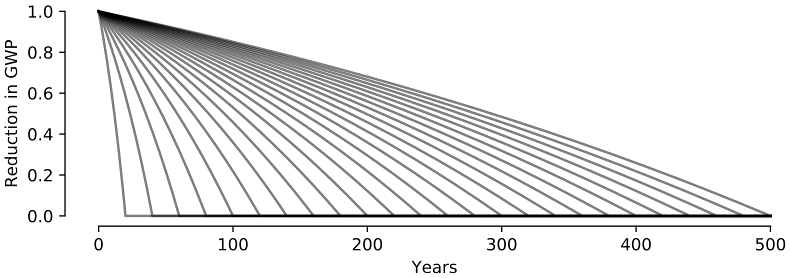

Figure B.4: Time adjustment vectors for different time horizons. The leftmost vector is for a TH of 20 years, and then increment by 20 all the way up to a TH of 500.

B.3 Calculation of inventory emissions

The greenhouse gas (GHG) emissions are first calculated for each material inventory item, i.e. each building material within the building's study scope. The emissions are calculated for each year from the year of construction until the final year of the time horizon (TH). In the calculations, both inventory data of each product, and the global study parameters p, given in C.1, are used. Here, the calculation of each emission source is described.

For each lifecycle phase, the emission sources s are represented by matrices, as shown in Figure **??**, with the inventory items, i, in the rows and years in the TH, y, in the columns: $\mathbf{A}_{s(i,y)}$, $\mathbf{B}_{s(i,y)}$, and $\mathbf{C}_{s(i,y)}$.

B.3.1 Biogenic carbon

It is assumed that the biomass comes from a sustainably managed forest kept under continuous rotation. Within the rotation period (the time span of a full regrowth and trees ready for harvest) the same amount of carbon will have been sequestered as was cut down. The uptake of CO_2 in year y is modeled by the first derivative of the Chapman-Richards (CR) growth function

$$f_{\mathrm{CR}}(y) = kpe^{-ky}(1 - e^{-ky})^{p-1}, \tag{3}$$

where $k = 0.23$, $p = 3$ are model parameters describing the growth rate and catabolism of the trees. Eq. (3) is multiplied by the CO_2 content of the material and then normalized to account for an assumed rotation period of 100 years

$$f_{\mathrm{bio},i}(y) = m_{\mathrm{CO}_2,i} \cdot f_{\mathrm{CR}}(y) / \sum_{y=0}^{100} f_{\mathrm{CR}}(y), \tag{4}$$

where $m_{\mathrm{CO}_2,i}$ is the mass of stored CO_2 in inventory product i. The regrowth will depend largely on the type of trees and climate. Different types of trees have different growth rates and periods of growth, with different parameterizations of this function. Here, the normalization reduces the importance of parameters k and p leaving a 100 year rotation period the most sensitive parameter.

Both the timing and the extent of oxidation of the biogenic carbon and its release into the atmosphere occur far into the future and are unknown. Here, it is assumed that 50% of the carbon stored in the materials is released into the atmosphere. Technological progress will lead to a 1% yearly reduction in this ratio.

Figure B.5 shows the biogenic carbon uptake, waste oxidation, and the combined effect, for a 1 kg wood product. Figure B.6 shows the same after the effects of time delay in a 100 year TH are included. Construction waste is not included in these figures, which would lead to an emission spike from incineration in the first year, and slightly higher emissions for following years; however, it is included in the results.

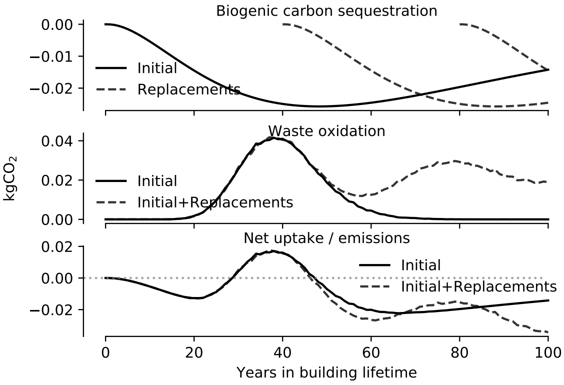

Figure B.5: Biogenic carbon uptake and release from 1 kg wood product before the effect of timing is considered.

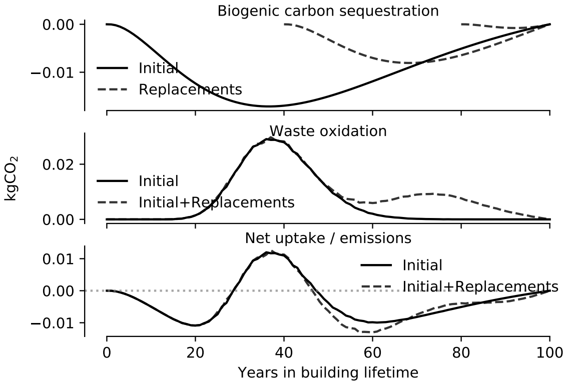

Figure B.6: Biogenic carbon uptake and release from 1 kg wood product. Effect of timing in a 100 year TH is considered.

B.3.2 Carbonation of cement products

The dynamic sequestration profile of carbonation follows the exponential decay function

$$f_{\mathrm{carbonation}}(y) = 1 - e^{-.03y}, \tag{5}$$

for the years y in the building lifetime, resulting in $\sim$ 50% uptake the first 25 years. An assumption of 0.1 kgCO$_2$ uptake per kg cement over a 100 years is made. These assumptions are based on information from [9]. To get the carbonation of inventory product i, eq. (5) is multiplied by a factor of 0.1 and the cement mass in the material, and then normalized to to ensure a correct total uptake over 100 years

$$f_{\mathrm{cem},i}(y) = 0.1 \cdot m_{\mathrm{cement,i}} \cdot f_{\mathrm{carbonation}}(y) / \textstyle\sum_{y=0}^{100} f_{\mathrm{carbonation}}(y), \tag{6}$$

where $m_{\mathrm{cement,i}}$ is the mass of cement in inventory product i. For building lifetimes longer than 100 years, the exponentially decaying uptake trend is continued beyond year 100.

B.3.3 The construction phase (A)

The construction phase involves producing all building materials, transporting them to the building site, and handling construction waste. Emissions in the operation and end-of-life phases are modeled based on construction phase quantities and emissions. Not all material gets used in the building, some fraction of it becomes construction waste. This means that an extra quantity of the material must be produced and transported, and the waste may be incinerated.

The production of materials is for simplicity placed in year zero, although materials might have been produced earlier. The production of material i per quantity q results in f kgCO$_2$e per functional unit (FU). The unit of the quantity and the FU can be kg, m, m^2, m^3, or pieces. The material quantity including construction waste is $(1 + p_{\mathrm{was}})$. The total quantity is multiplied with f to get the emissions from production

$$\mathbf{A}_{\mathrm{pro}(i,\,0)} = (1 + p_{\mathrm{was}}) q_i f_i. \tag{7}$$

The transport of materials from the factory to the building site can be split among multiple transportation modes, with transport distances $d_1, d_2, d_3...$, [km] and transport mode emission intensities $t_1, t_2, t_3...$ per weight and distance [kgCO$_2$e/kgkm]. After the functional unit of the material quantity is converted to kg by multiplication with the density ρ [kg/FU], the transport emissions of material i can be calculated as the sum of transport to the building site and return of the waste to the waste handling

$$\mathbf{A}_{\mathrm{tra}(i,\,0)} = q_i \rho_i [(1 + p_{\mathrm{was}})(d_{i,1} t_{i,1} + d_{i,2} t_{i,2} + d_{i,3} t_{i,3} + ...) + p_{\mathrm{was}} \cdot p_{\mathrm{EoLdist}} \cdot \mu_{t_i}], \tag{8}$$

where p_{EoLdist} is the transport distance to waste handling, and μ_{t_i} is the mean of $t_1, t_2, t_3...$ for product i.

The construction waste is incinerated if the material is containing carbon

$$\mathbf{A}_{\mathrm{was}(i,\,0)} = q_i \rho_i p_{\mathrm{was}} p_{\mathrm{inc}} p_{\mathrm{cc}} \frac{44}{12}, \tag{9}$$

where p_{inc} is the fraction of the stored carbon released into the atmosphere, p_{cc} is the carbon content of the material, and $\frac{44}{12}$ is the molecular fraction of CO$_2$ per C atom. The carbon contents of the materials are assigned according to which material category the products are in. If the product is within the material categories considered to be biogenic and fossil, as given in C.2, fixed carbon contents p_{ccbio} and p_{ccnonbio}, given in C.1 are assumed for biogenic products and and fossil products, respectively.

B.3.4 The operation phase (B)

The operation phase (use phase) begins when the construction phase ends, and the building is taken into use. Building materials gradually need to be replaced, including production, transport, and waste incineration of the replaced products. The timing of these future emissions is distributed statistically, and thus spread out over many years. All emissions are first calculated without dynamic effects (technological improvements and delayed emissions); these are applied in a later step.

The production of materials used for replacements is the sum of all the statistically distributed replacements during the building lifetime

$$\mathbf{B}_{\mathrm{pro}(i)} = \sum_{l \cdot n}^{2L} \mathbf{A}_{\mathrm{pro(i,0)}} \sim \chi_l^2, \qquad \text{for } y \leq L \tag{10}$$

where L is the building lifetime, l is the lifetime of the material, and n is an integer.

The transport of the replacement materials from the factory to the building, and of the replaced materials to end-of-life treatment is

$$\mathbf{B}_{\text{tra}(i)} = \sum_{l \cdot n}^{2L} \mathbf{A}_{\text{tra(i,0)}} \sim \chi_l^2, \qquad \text{for } y \leq L \tag{11}$$

End-of-life waste incineration is considered for all replaced components, and is including construction waste

$$\mathbf{B}_{\text{was}(i)} = \sum_{l \cdot n}^{2L} (1 + p_{\text{was}}) q_i \rho_i p_{\text{inc}} p_{\text{cc}} \frac{44}{12} \sim \chi_l^2, \qquad \text{for } y \leq L \tag{12}$$

Additionally, carbon sequestration occurs continuously throughout this period: the regrowth of trees sequesters carbon into biomass through photosynthesis, and cement products in the building undergo carbonation, i.e. chemical reactions between CO_2 from surrounding air react chemically with $Ca(OH)_2$ in the cement product to form $CaCO_3$ and H_2O. Biogenic carbon sequestration during the years of operation is

$$\mathbf{B}_{\text{bio}(i)} = f_{\text{bio},i} + \sum_{\text{replacements}} f_{\text{bio},i}, \qquad \text{for } y \leq L \tag{13}$$

where the replacements take place every $l \cdot n$ years. The carbon uptake from replacements is equal to the uptake from initial material use, but is shifted so that they begin in the year of the replacement.

Carbon uptake in cement products is calculated for materials in the material categories *concrete, cement* by

$$\mathbf{B}_{\text{cem}(i)} = f_{\text{cem},i}. \tag{14}$$

For the material category *concrete*, the cement content is determined by $p_{\text{cem/con}}$. There are no replacements of cement products within the building lifetime.

B.3.5 The end-of-life phase (C)

End-of-life processes are related to the demolition of the building when its operational lifetime ends. The end-of-life processes are included only if the TH is longer than the building lifetime. Because emissions are time-discounted according to a dynamic GWP_{TH}-methodology, the warming effect of processes occurring in the last year of the TH and beyond will be zero. However, since the timing of all future emissions are statistically distributed, there is a probability that some end-of-life processes are occurring before the end of the TH even for a building lifetime equal to or longer than the TH.

The transport of all building materials to the waste handling facilities is modeled by

$$\mathbf{C}_{\text{tra}(i,\,y)} = q_i \rho_i p_{\text{EoLdist}} \mu_{t_i} \sim \chi_L^2. \tag{15}$$

The waste incineration of the carbon containing products is modeled as

$$\mathbf{C}_{\text{was}(i,\,y)} = q_i \rho_i p_{\text{cc}} p_{\text{inc}} \frac{44}{12} \sim \chi_L^2. \tag{16}$$

The biogenic carbon sequestration happening in the end-of-life phase is the same as in the operation phase, but are those that happen after the building lifetime L ends

$$\mathbf{C}_{\text{bio}(i,\,y)} = f_{\text{bio},i} + \sum_{\text{replacements}} f_{\text{bio},i}, \qquad \text{for } y > L \tag{17}$$

for the years y after the building lifetime but within the TH.

B.4 Applying dynamic effects

Each emission source is first calculated for each inventory item for each year in the time horizon, which results in one unadjusted emission source matrix $\mathbf{E}_{s(i,y),\text{unadj.}}$ for each emission source s, with the dimensions *inventory*$\times$*year*.

Each emission source matrix is then adjusted for technology improvements and time discounting by multiplying each row i with the technology vector $\omega_{s(i)}$, and by the time-discounting vector τ

$$\mathbf{E}_{s(i),\text{adj.}} = \mathbf{E}_{s(i),\text{unadj.}} \omega_{s(i)} \tau, \tag{18}$$

where $\omega_{s(i)}$ specify the technological development of inventory i for emission source s, and τ is the same for all inventory items and emission sources. Similarly, emissions that are technology adjusted but not adjusted for time delay are calculated as

$$\mathbf{E}_{s(i),\text{techadj.}} = \mathbf{E}_{s(i),\text{unadj.}} \omega_{s(i)}. \tag{19}$$

B.5 Calculation of subpart emissions and metrics

Each building can be separated into *subparts*. A subpart is a subset of the material inventory. Emissions are calculated for each subpart. In addition, average metrics that contain information about the subpart emissions are calculated. These metrics are: the quantity Q [kg] (the total mass); the distance D [km] (the weighted average distance from factory to building site); the emission factors α_s (phase A), β_s (phase B), and γ_s (phase C) [kgCO$_2$e/kg] for each emission source s (emission intensity per weight of the subpart); the tech factors ω_s (the total reduction effect of the modeled future technology developments); and the delay factors τ_s (the total reduction effect of the delay within the TH).

B.5.1 Subpart emissions, quantity, and distance

The inventory items i in the emission source matrices $\mathbf{E}_{s,\text{unadj.}}$, $\mathbf{E}_{s,\text{techadj.}}$, and $\mathbf{E}_{s,\text{adj.}}$ are grouped together into building subparts, which is simply a collection of inventory items. The emissions for each subparts is the sum of the emissions of its inventory items. Inventory items are grouped into subparts according to their belonging to the predefined building elements and material categories. This results in both unadjusted (E_s) and adjusted ($E_{s,\text{adj.}}$) emissions for each subpart, for each building. In addition, the total quantity of each subpart is calculated

$$Q = \sum_{i \in s} q_i \rho_i, \tag{20}$$

and so is the weighted total distance of transport of the materials in the subpart

$$D = \frac{\sum_{i \in s} q_i \rho_i (d_{i,1} + d_{i,2} + d_{i,3} + ...)}{\sum_{i \in s} q_i \rho_i} \tag{21}$$

The emission factors, tech factors, and delay factors of each subpart can now be calculated. The following calculations are performed for each subpart.

B.5.2 Emission factors

The emission factors for the construction phase, α, are calculated as $\mathbf{A}_s/Q$. It does not matter if the unadjusted $\mathbf{A}_s$ or the adjusted $\mathbf{A}_{s,\text{adj.}}$ are used, since these are equal for the construction phase (no technology improvement or time delay has happened in year zero).

The emission factors for the operation phase, β, are calculated as $\mathbf{B}_s/Q$. The unadjusted emissions must be used, since the emission factors represent the unadjusted emission intensities.

The emission factors for the end-of-life phase, γ, are calculated in the same way, as $\mathbf{C}_s/Q$. The unadjusted emissions must be used, since the emission factors represent the unadjusted emission intensities.

B.5.3 Tech factors

The tech factors ω are all calculated as a fraction of the tech adjusted emissions to the unadjusted emissions. For example, ω_{tra} is calculated as

$$\omega_{\text{tra}} = (\mathbf{B}_{\text{tra, techadj.}} + \mathbf{C}_{\text{tra, techadj.}})/(\mathbf{B}_{\text{tra, unadj.}} + \mathbf{C}_{\text{tra, unadj.}}) \tag{22}$$

when the tech factor should represent both future phases, and as

$$\omega_{\text{Btra}} = \mathbf{B}_{\text{tra, techadj.}}/\mathbf{B}_{\text{tra, unadj.}} \tag{23}$$

if the tech factor should only represent the B-phase. More generally, the tech factors are calculated as

$$\omega_s = (\mathbf{B}_{s,\text{techadj.}} + \mathbf{C}_{s,\text{techadj.}})/(\mathbf{B}_{s,\text{unadj.}} + \mathbf{C}_{s,\text{unadj.}}). \tag{24}$$

B.5.4 Delay factors

The delay factors τ are calculated as a fraction of the adjusted emissions to the technology adjusted emissions. For example, τ_{tra} is calculated as

$$\tau_{\text{tra}} = (\mathbf{B}_{\text{tra, adj.}} + \mathbf{C}_{\text{tra, adj.}})/(\mathbf{B}_{\text{tra, techadj.}} + \mathbf{C}_{\text{tra, techadj.}}) \tag{25}$$

when the delay factor should represent both future phases, and as

$$\tau_{\text{Btra}} = \mathbf{B}_{\text{tra, adj.}}/\mathbf{B}_{\text{tra, techadj.}} \tag{26}$$

if the delay factor should only represent the B-phase. More generally, the delay factors are calculated as

$$\tau_s = (\mathbf{B}_{s,\text{adj.}} + \mathbf{C}_{s,\text{adj.}})/(\mathbf{B}_{s,\text{techadj.}} + \mathbf{C}_{s,\text{techadj.}}). \tag{27}$$

C Model definitions and assumptions

C.1 Global study parameters

Model assumptions and data is harmonized by setting some parameters equal for all case studies in the dataset. These global study parameters, presented in Table C.2, ensure that the calculations of each study is compatible with that of every other.

Table C.2: Global model parameters and their values. L and T are varied in the results. Sensitivity of the parameters is tested in the global sensitivity analysis (GSA).

Parameter		Value	Description
Building lifetime	L	80 years	Years from construction to end-of-life.
Time horizon	T	100 years	The years over which global warming are accounted for.
Waste fraction	p_{was}	.1	Ratio of construction waste mass to total building mass.
Incineration fraction	p_{inc}	.5	Fraction of construction waste carbon released into the atmosphere.
Waste distance	p_{EoLdist}	50 km	Distance from the building to the waste handling.
Carbon content bio-products	p_{ccbio}	.5	Carbon content of biogenic products.
Carbon content non-bio	p_{ccnonbio}	.8	Carbon content of fossil carbon products.
Cement fraction	$p_{\text{cem/con}}$	.1	Fraction of cement in concrete products.
Production technology	p_{dfpro}	.01	Decay factor production.
Transport technology	p_{dftra}	.02	Decay factor transport.
Waste technology	p_{dfwas}	.01	Decay factor waste.
PV production technology	p_{dfPV}	.037	Decay factor PV panels.
Energy technology	p_{dfene}	.03	Decay factor energy.

Sensitivity of the parameters is tested in the global sensitivity analysis (GSA). When all parameters are allowed to vary within the intervals given in the Figure C.7 (with uniform distributions), the TH is the most sensitive parameter. The TH is a normative choice, which depends on the goal of the analysis, and is thus not dependent on a precise estimate. The remaining parameters are possible to quantify empirically. Of those, the ones that contribute significantly to model variance depend on the chosen TH. For all THs between 20 and 500 tears, the most sensitive parameters (in addition to the TH) are the *building lifetime* and *carbon content of biomaterials*, followed by the *fraction of construction waste incinerated*, and the *decay factor of waste* (determining technological improvements). The remaining parameters contribute much less to model uncertainty.

In a fixed TH of 20 years, the importance of precisely determining parameters changes: the *fraction of waste* and the *fraction incinerated* are responsible for most of the variation in model results.

If the TH is fixed at 100 years, again, the importance of the parameters changes: the rotation period, fraction incinerated, fraction of waste carbon content of bioproducts, decay factor of waste are highly influential.

The *fraction of waste* and the *fraction incinerated* are quite sensitive in all THs. A study of the waste fraction in the Dutch construction industry estimated an average of 9% waste by weight of the purchased construction materials [10]. This is used as a basis for the assumed waste fraction of 0.1, which is assumed equal for all material categories. This is an imprecise estimate from an outdated source, and further research is needed to get more precise estimates. Further research is also needed to precisely determine the other sensitive parameters. One way to avoid large parts of the uncertainty is to use project specific values for waste fractions, incineration fractions, carbon contents, and rotation periods of each material inventory item. This would yield much more precise results than assuming average values for all materials.

C.2 Material categorization

Materials are manually categorized based on a judgment of the material name, into the categories: *’Steel’, ‘Concrete’, ‘Timber’, ‘Windows’, ‘Gypsum’, ‘Doors’,’Insulation’, ‘Flooring, tiles’, ‘Carpet’, ‘Plastics’, ‘Asphalt’, ’Glass’, ‘Aluminium’, ‘Membrane’, ‘Timber, CLT’, ‘Cement’, ’Linoleum’, ‘Timber, Gluelam’, ‘XPS’, ‘Glass wool’, ‘Brick’, ’Plywood’, ‘Laminate’, ‘Other’, ‘Gypsum, plaster’, ‘EPS’, ’Insulation, mineral’, ‘Vinyl’, ‘Cork’, ‘Flooring, parquet’, ’Acoustic insulation’, ‘Sink’, ‘Sylomer’, ‘Wood wool’, ’Flooring, ceramic tiles’, ‘Flooring’, ‘Ceiling’, ‘PV panel’, ’Coating’, ‘Bitumen roofing’, ‘Gravel’, ‘Copper’, ’Technical installations’, ‘Elevator’, ‘Rock’, ‘Paint’, ‘Granite’, ’ST collector’, ‘Hot water tank’, ‘Heat pump’, ‘Rubber’*

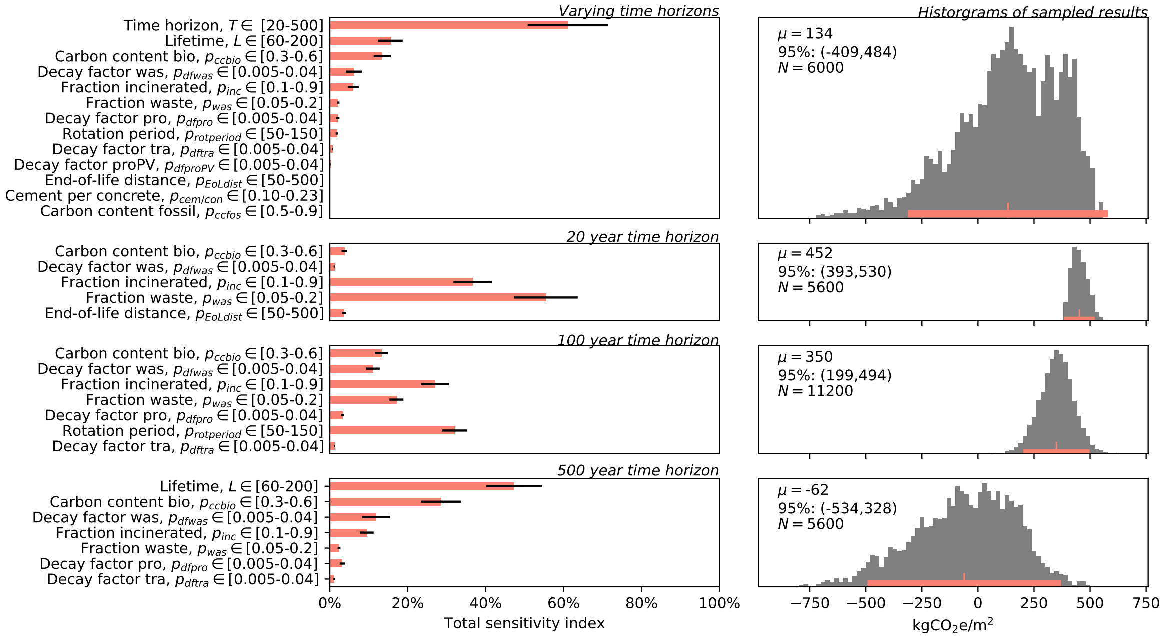

Figure C.7: The relative contribution of global parameters to total model variance (left) calculated with Sobol analysis based on the Saltelli-sampled model results (right). The results are the total emissions from all sources over all years in the TH for the entire inventory in the dataset (all buildings). The black lines (left) show the 95% confidence interval of the sensitivity indices. The orange bar (right) shows the 95% confidence interval of the sampled results.

Materials are considered biogenic if they are in the categories *’Cork’, ‘Flooring, parquet’, ‘Timber’, ‘Timber, CLT’,’Plywood’,’Laminate’,’Linoleum’,’Timber, Gluelam’,’Wood wool’,’Rubber’.*

Materials are considered fossil if they are in the categories *‘Sylomer’, ‘XPS’, ‘Plastics’, ‘EPS’, ‘Membrane’, ‘Vinyl’, ‘Carpet’.*

D Sensitivity analyses

The principal sensitivity analysis can be found in the main paper (and in C.1), where model parameters are analyzed in a variance-based global sensitivity analysis. There, all parameters are varied simultaneously across their entire parameter spaces, which ranks parameters according to their relative contribution to model variance. Here, some of the parameters found to be influential are explored further by varying one parameter at a time.

The modeling choices of *replacement distribution* (the years that replacements take place), *building lifetime* (years of operation before the building is demolished), *time horizon* (years that emissions matter), and the remaining *parameter values*, are affecting model results. Here, the sensitivities of these the modeling choices are tested.

D.1 Choosing replacement distributions

The exact year that a future emission will take place is uncertain, and the further into the future the more uncertain that parameter becomes. To take account of that randomness, the year of future emissions can be represented by a random variable such as the normal or the chi-square distributions. Six different methods are tested. In Figure D.8, the replacement of a product with 35 years service lifetime is used as an example. The normal distribution (top) has constant variance, and does therefore not take into account that uncertainties increase further into the future. This can be modeled by a normal distribution with increasing variance, or similarly, by a chi-square distribution (middle). In the figure, the normal and chi-square distributions are shown in two versions: the 'cut-off' and 'no cut-off' versions. The 'cut-off' assumes that no replacements take place beyond the building lifetime. However, the building lifetime is highly uncertain, and a sharp cut-off at the end of the building lifetime therefore does not make sense. The 'no cut-off' version acknowledges that the building lifetime is an unknowable parameter, and therefore includes parts of the emissions from replacements also after the building lifetime.

Traditionally, the years of replacements are in building LCAs treated as discrete integer variables, also shown in Figure D.8 (bottom). If the last replacement has a material lifetime longer than the remaining building lifetime, then it may alternatively be treated as the fraction of the remaining lifetime (shown in gray). Replacements beyond the building lifetime are omitted completely.

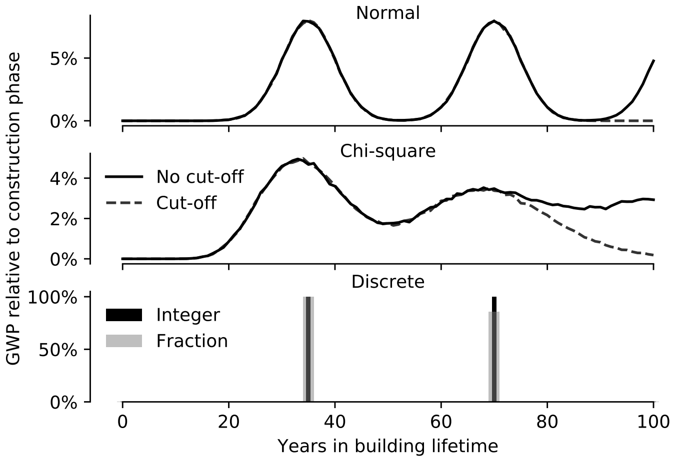

Figure D.8: The different approaches used for modeling the emissions from replacements of a material over the buildings lifetime. The example product with 35 years lifetime is replaced based on (a) a normal distribution, (b) a chi-square distribution, or (c) a traditional discreteyear-of-replacement'-approach. In addition, the effect of cut-off in last year of lifetime is demonstrated. If replacement happened one year earlier, then the two would be equal.

Emissions occurring in the future are uncertain, and so are their time of occurrence. The modeling choice of the timing will affect the results, and is therefore important to get right. The effect of different modeling approaches is tested here. Figure D.9 shows the effect of the different approaches to modeling the timing of replacements, and how it changes with material lifetime and building lifetime. The dynamic effects (technological improvements and delayed emissions) are not included. The abrupt changes in the *integer distribution* makes this particular solution a bad choice, since a change in material lifetime of one year will add or remove one replacement. E.g. a material lifetime of 99 years with a building lifetime of 100 will induce one replacement, while a material lifetime of 100 will induce none. Clearly, the number of replacements should be a smooth transition when the material lifetime changes. This problem is solved with the *fraction distribution*, but it places the estimate low; replacements can not occur earlier than the estimated material lifetime, and they can not occur beyond the postulated building lifetime. The years of replacements are unknown, and should be represented by a random variable. The *normal distribution* gets it better: the abrupt changes are smoother, however, they still display an uneven effect. The chi-square distribution is smooth, and not underestimated, i.e. it includes the probability of early replacements, as well as late ones. The normal distribution will achieve similar results as the chi-square if the variance is a function of material lifetime. The cut-off variations of the normal and chi-square distributions display this same abrupt changes as the integer distribution; this effect makes them undesirable.

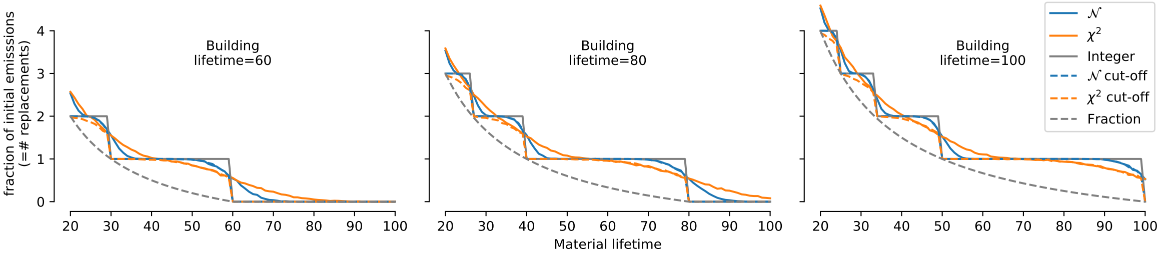

Figure D.9: Different approaches to modeling the timing of replacements, and how it changes with material and building lifetime. No technological development and no time delay adjustments.

However, the effect of the choice of replacement distribution decreases when technology improvements and time discounting is considered, and it further decreases with longer building lifetime. Figure D.10 shows this convergence of distributions when dynamic effects are included.

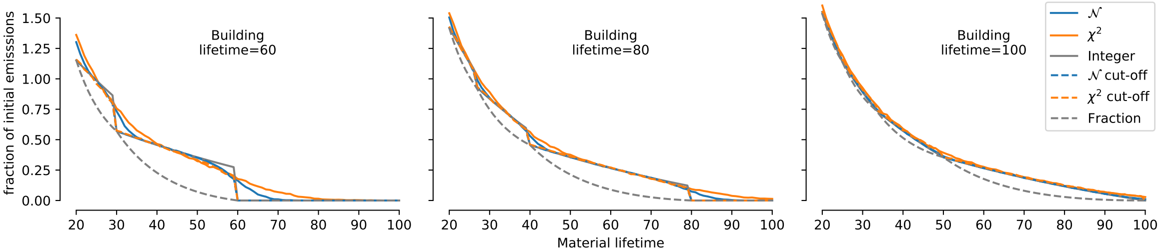

Figure D.10: Different approaches to modeling the timing of replacements, and how it changes with the lifetime of the material and of the building. Technology and time delay adjustments considered.

In conclusion, the chi-square distribution, or a normal distribution with increasing variance, have the best properties for modeling the timing of replacements. An integer number of replacements should be avoided, and solving this problem by treating the last replacement as a fraction will underestimate the likely impacts of replacements. Although the effects are still present, they will become less prominent when technology improvements and time discounting are included, and with increasing building lifetimes.

D.2 Choosing time horizon

The choice of time horizon will depend on the purpose of performing the LCA. Is it the global warming impact of the building over 20 years, 100 years, or 500 years that is most relevant in the context that the LCA is performed? Figure D.11 shows the results for time horizons in the range 20-100 years for a building with a 80 year lifetime. Figures D.12-D.13 show equivalent calculations for lifetimes of 60 and 120 years. The A-phase is independent of TH. The B-phase increases with longer THs. The C-phase increases slightly with longer THs, and more so for short building lifetimes. The total emission results varies little with different building lifetimes, it is thus the TH, and not the building lifetime which is the most important parameter.

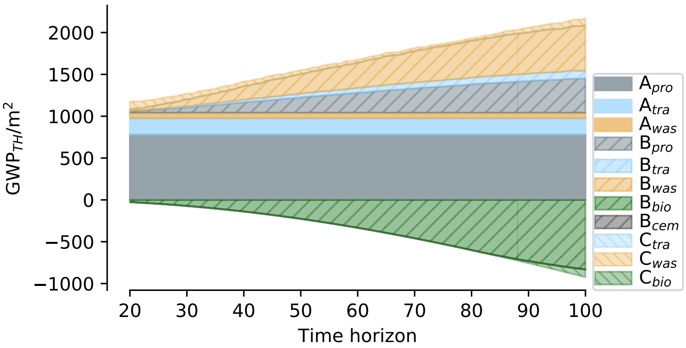

Figure D.11: Changing time horizons for a building with 80 year lifetime.

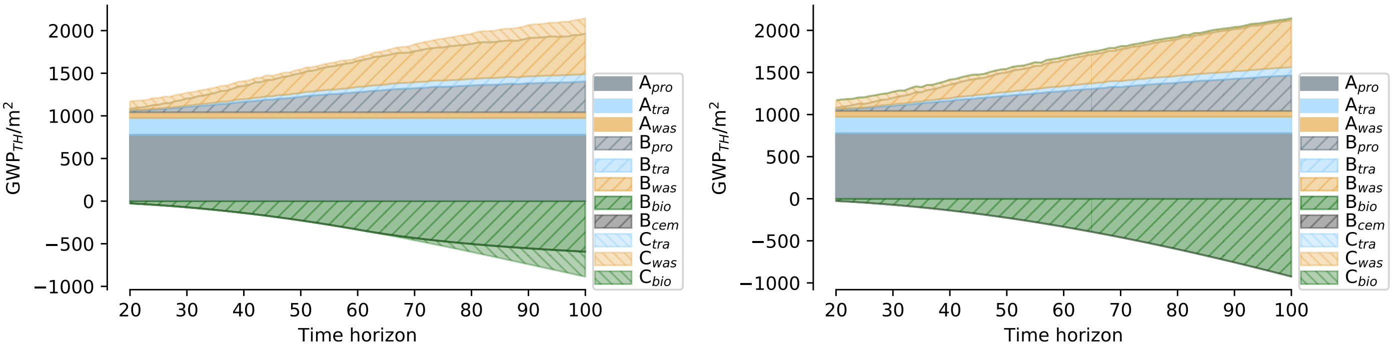

Figure D.12: Changing time horizons for a building with 60 year lifetime.Figure D.13: Changing time horizons for a building with 120 year lifetime.

D.3 Choosing building lifetime

One of the most uncertain parameters in a building LCA, is the building lifetime. It is impossible to know how long the building will be standing before it reaches its end-of-life phase. The choice of building lifetime is more often based on convention than on the buildings physical lifetime. Figure D.14 shows the effect of varying building lifetimes on the cumulative results, when the TH is fixed at 100 years. Figures D.15-D.16 show equivalent calculations for THs of 20 and 500 years. The A-phase is independent of lifetime. Short building lifetimes lead to lower impact from the B-phase and higher impact from the C-phase. Biogenic uptake and emissions are somewhat greater with longer lifetimes due to the additional replacement materials used. Apart from that, biogenic uptake is divided differently between the B and C phases (C phase begins after building lifetime ends). The effect of a clearly defined TH on reducing the sensitivity of the building lifetime can be clearly seen when comparing the 20, 100, and 500 year THs. With a long or infinite TH there is larger variation with building lifetime. With a shorter TH the variation is smaller. Furthermore, in the 100 year TH the sensitivity of building lifetime is very small for building lifetimes of more than 60 years, and very few buildings have shorter lifetimes than that. This means that the lifetime of the building is *irrelevant* for the warming effect taking place the first 100 years after construction.

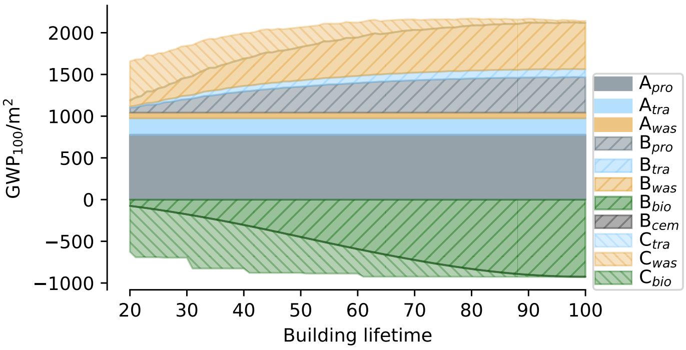

Figure D.14: Changing building lifetimes with a 100 year time horizon.

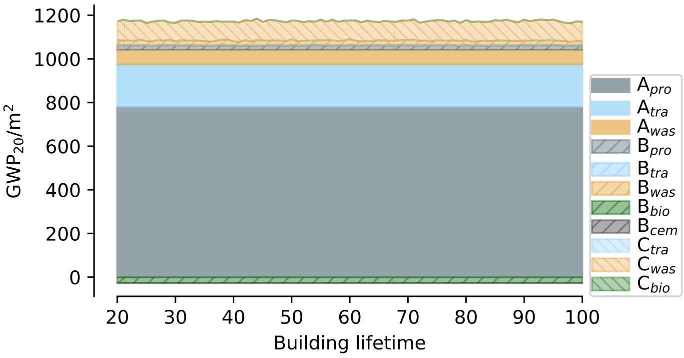

Figure D.15: Changing building lifetimes with a 20 year time horizon.

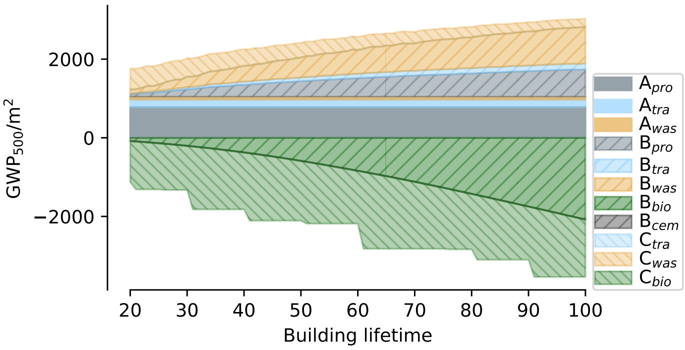

Figure D.16: Changing building lifetimes with a 500 year time horizon.

E Supplementary results

E.1 Distribution of emissions for all buildings

Figure E.17 shows the distributions of total emissions, total of each lifecycle phase, and total of each emission source, for building element 2: ‘Envelope, foundations, and structure’ in all buildings.

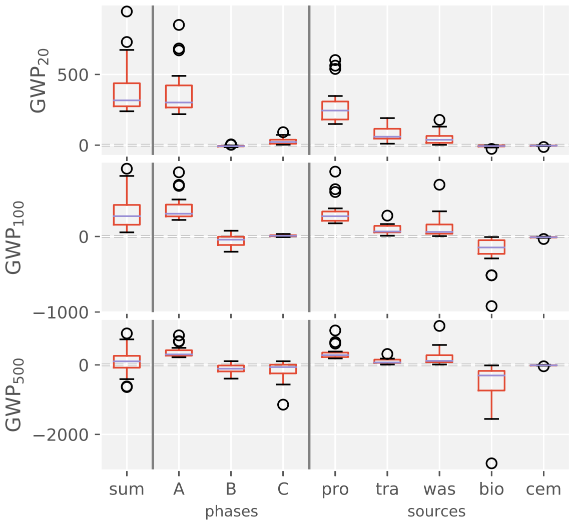

Figure E.17: Distributions of emissions for all buildings. Three different THs, 80 year building lifetimes. Total sum, sum of each lifecycle phase, and sum of each emission source.

E.2 Correlation between results

Figure E.18 shows the Pearson correlation of the emission results and metrics.

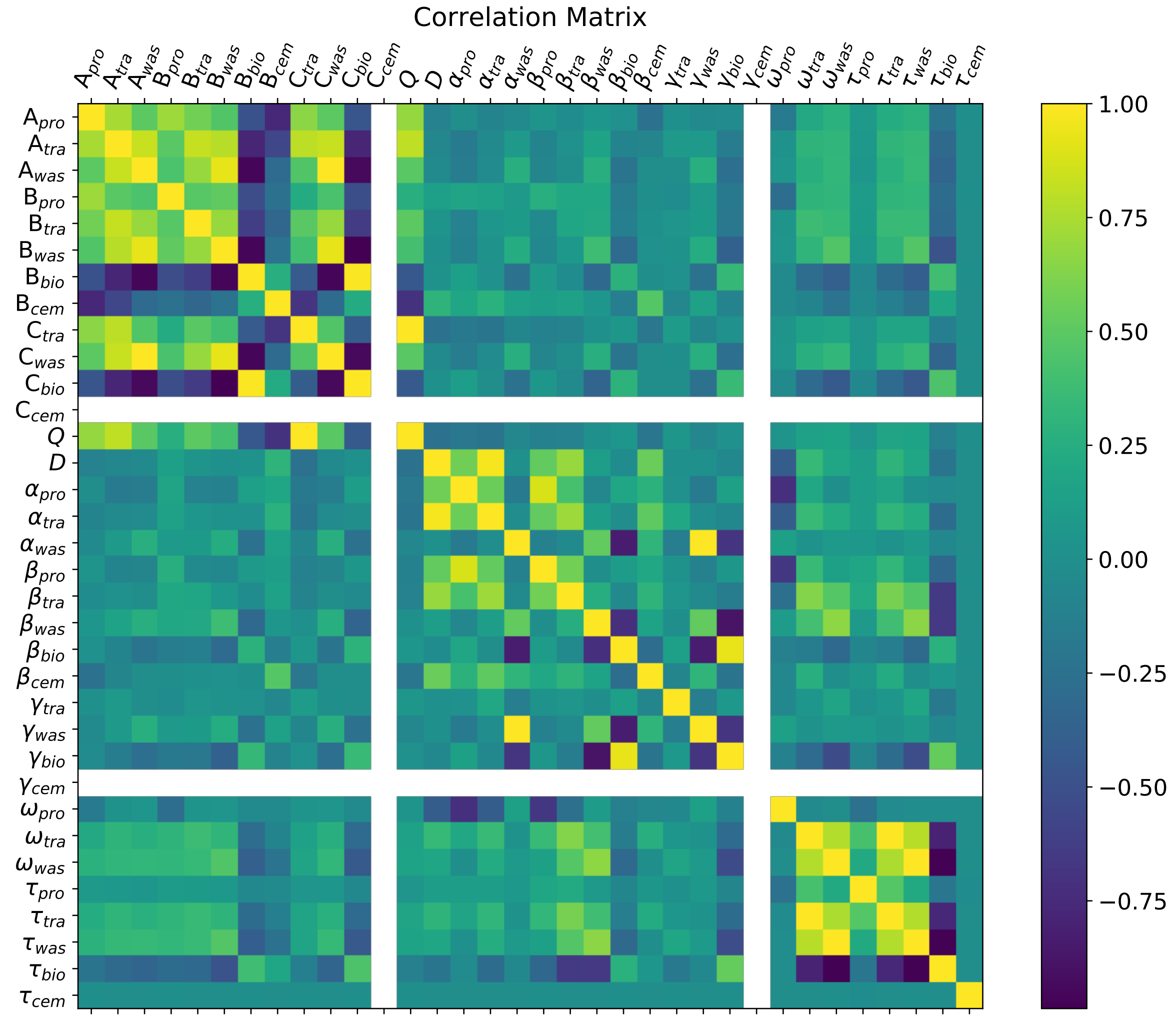

Figure E.18: The correlation matrix of the emissions, metrics, and adjustment factors for building element 2: ‘Envelope, foundations, and structure’. Each box shows the 25th, 50th, and 75th percentiles.

E.3 Statistical emissions and metrics for various time horizons

E.3.1 Typology building types

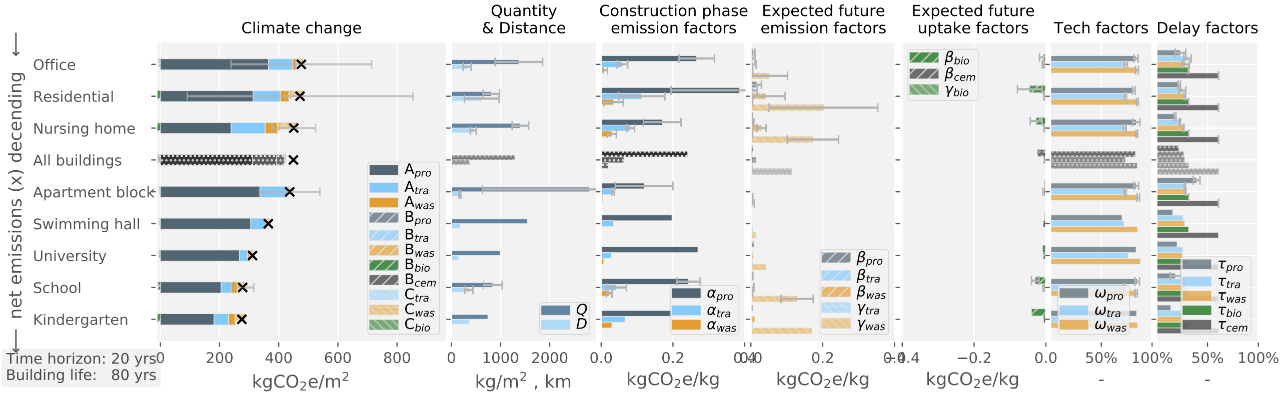

Figure E.19: 20 year time horizon.

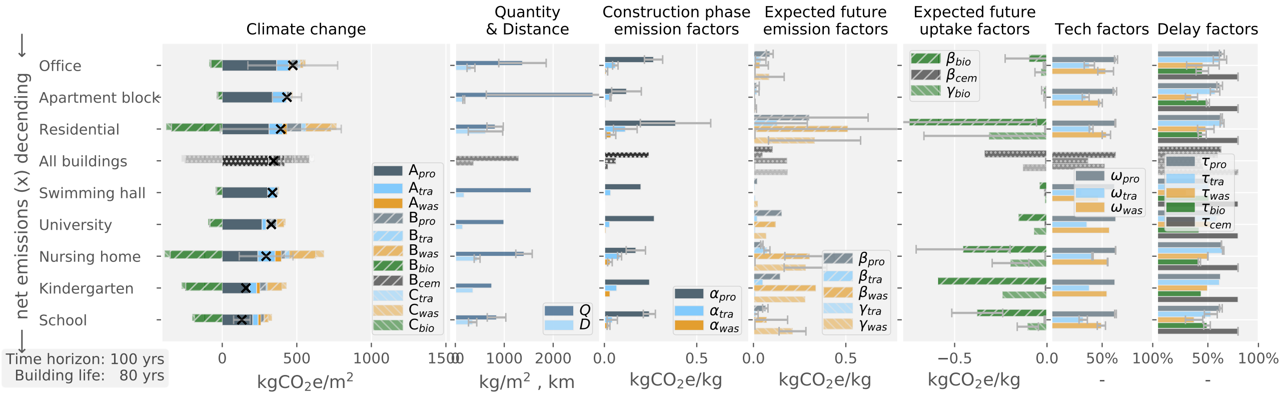

Figure E.20: 100 year time horizon.

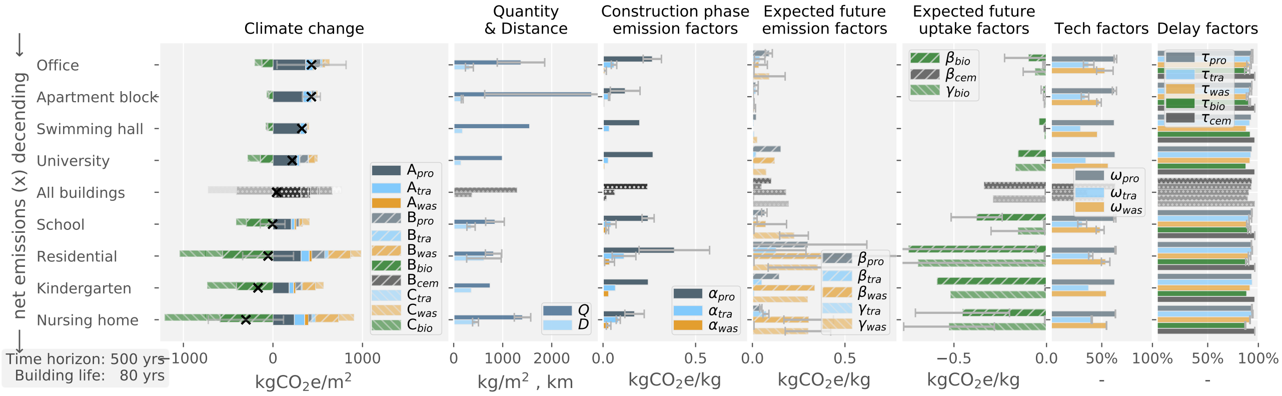

Figure E.21: 500 year time horizon.

E.3.2 Timber and concrete building types

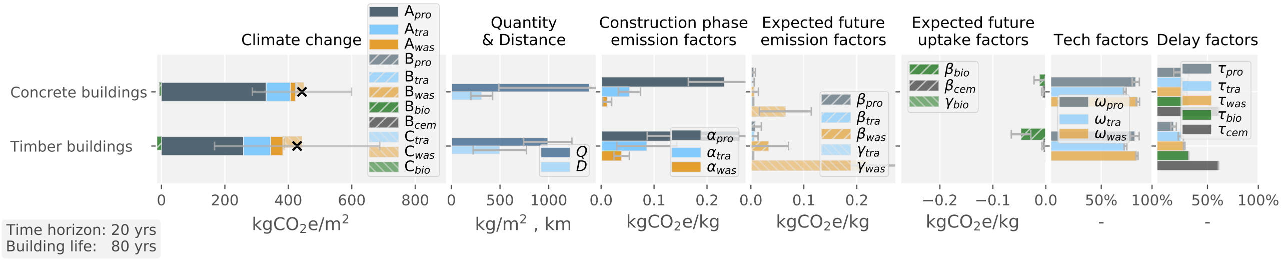

Figure E.22: 20 year time horizon.

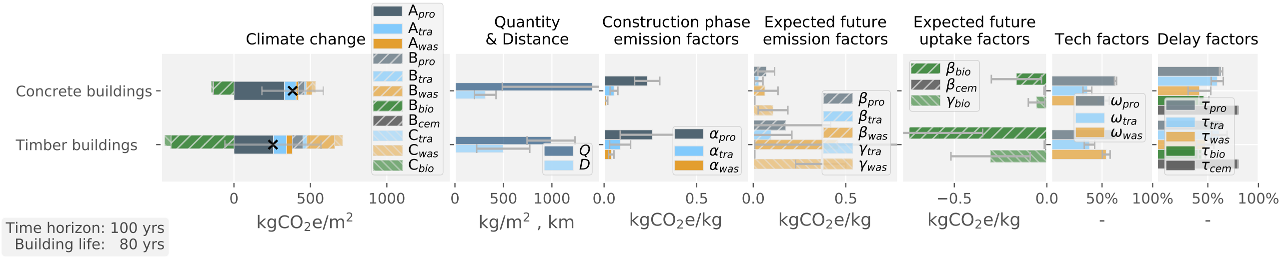

Figure E.23: 100 year time horizon.

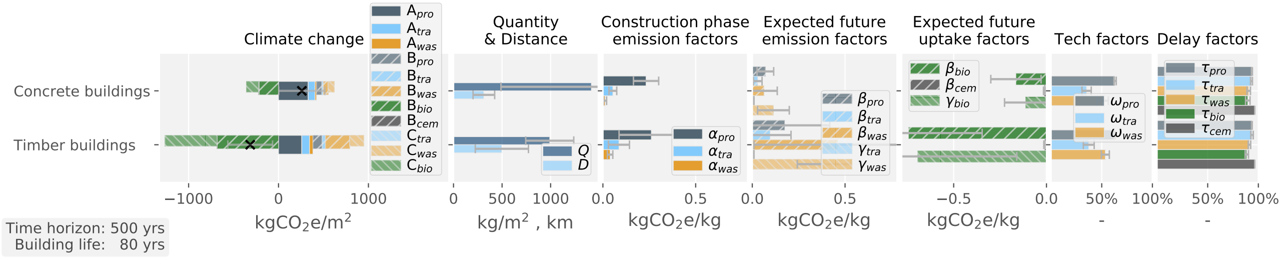

Figure E.24: 500 year time horizon.

E.3.3 Building element subparts

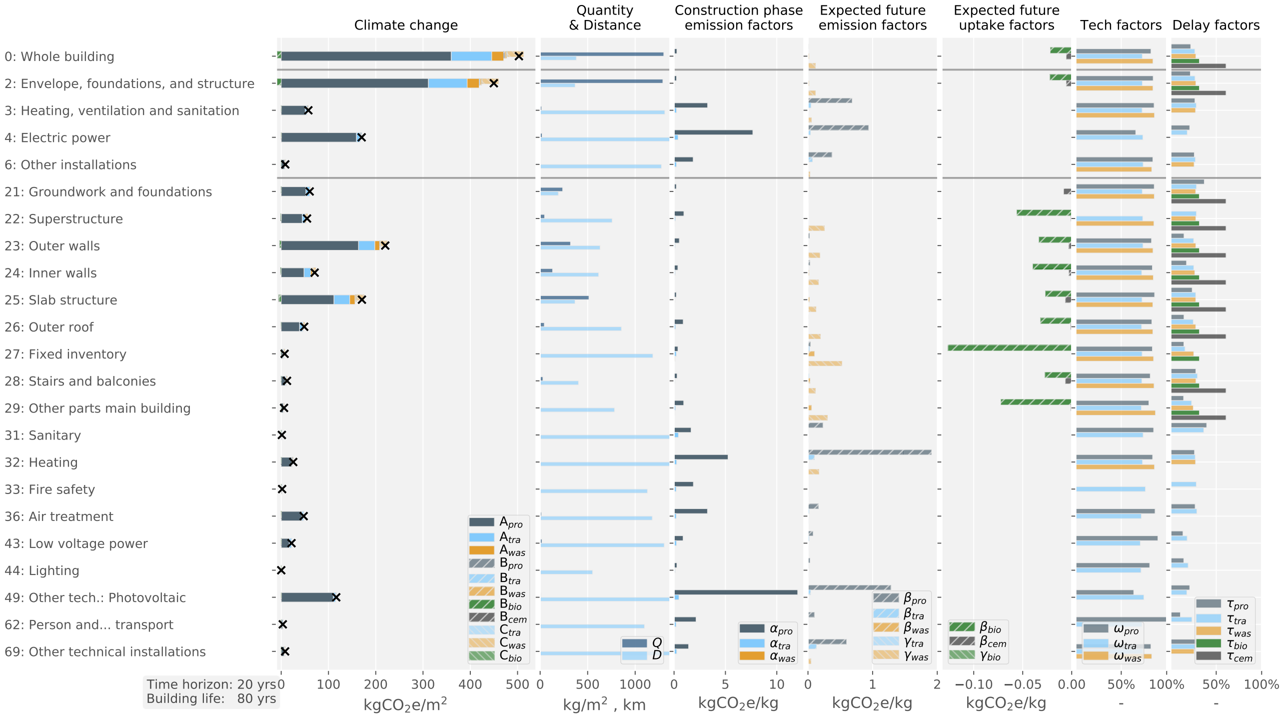

Figure E.25: 20 year time horizon.

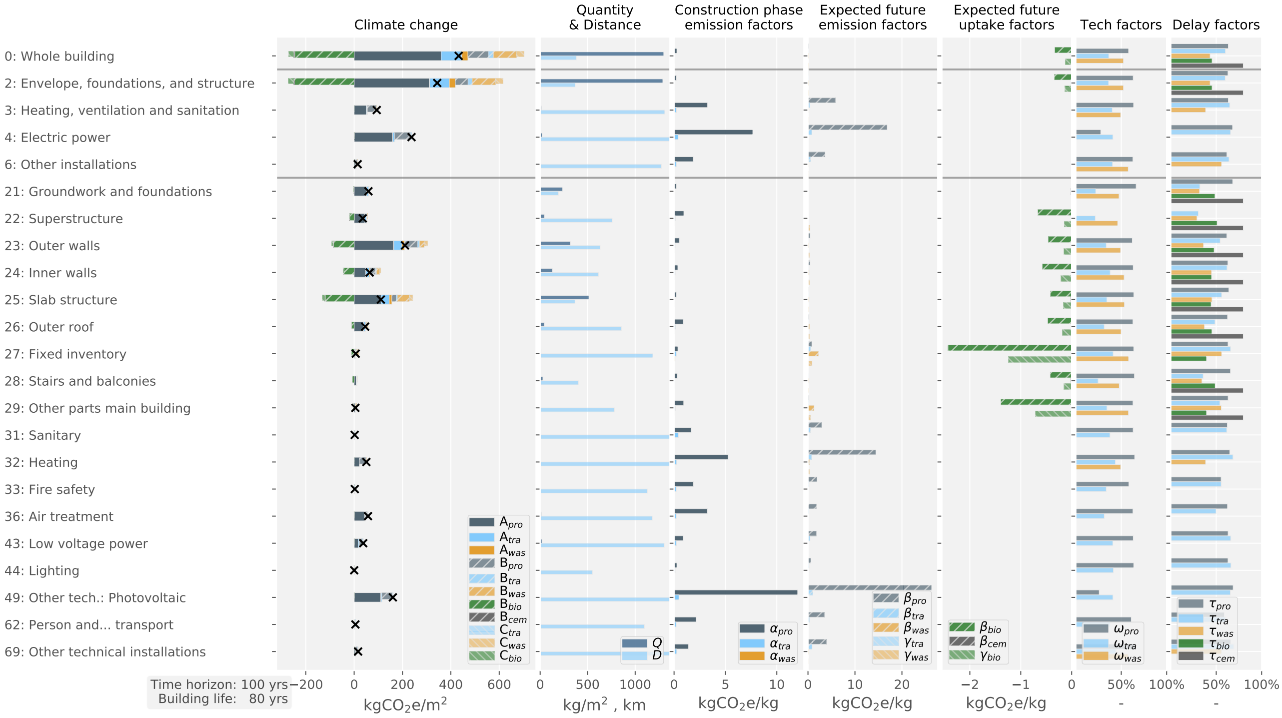

Figure E.26: 100 year time horizon.

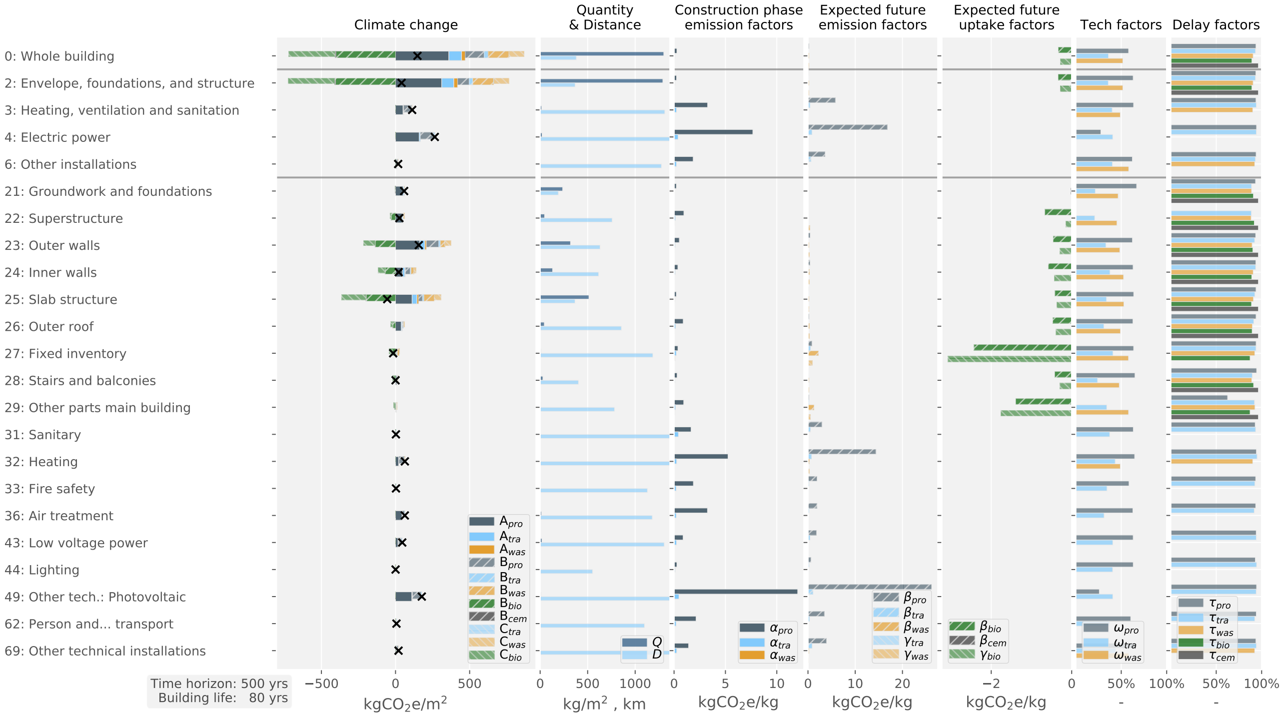

Figure E.27: 500 year time horizon.

E.3.4 Material category subparts

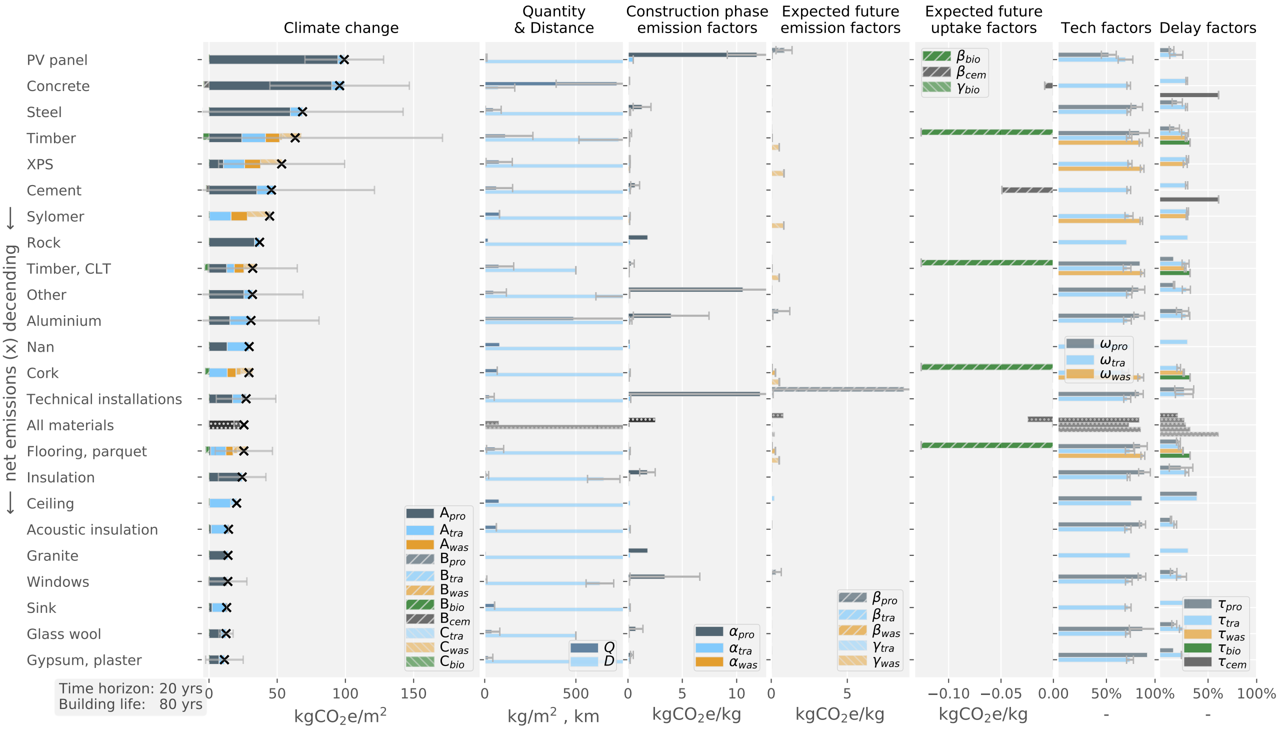

Figure E.28: 20 year time horizon.

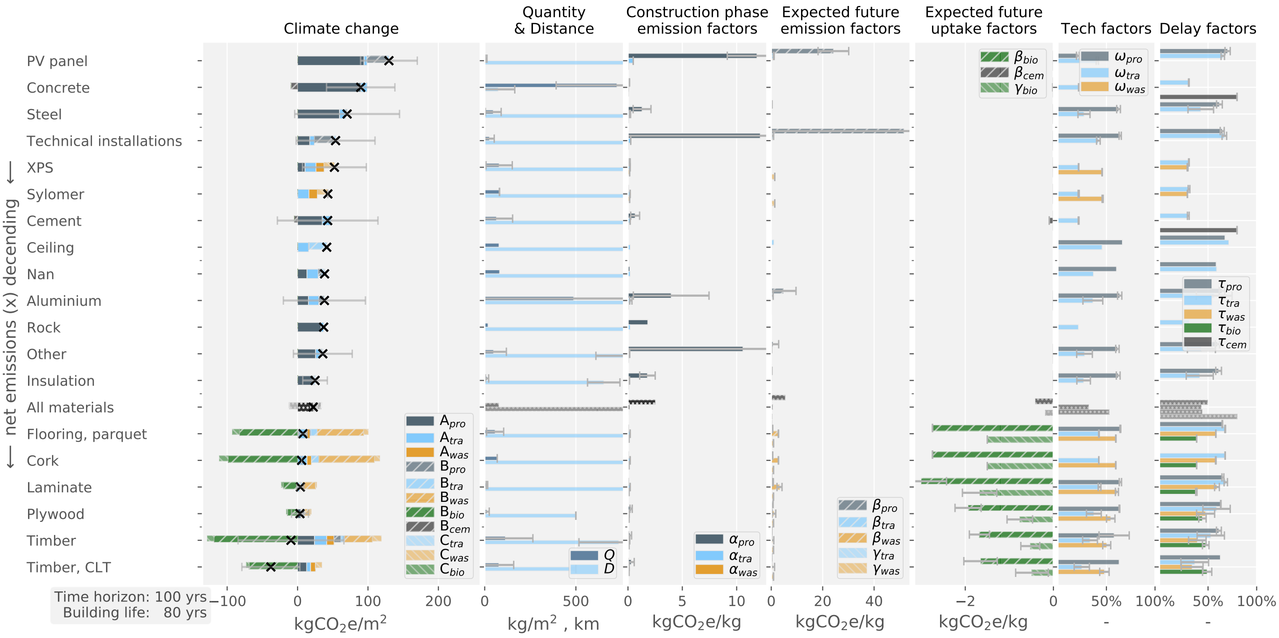

Figure E.29: 100 year time horizon.

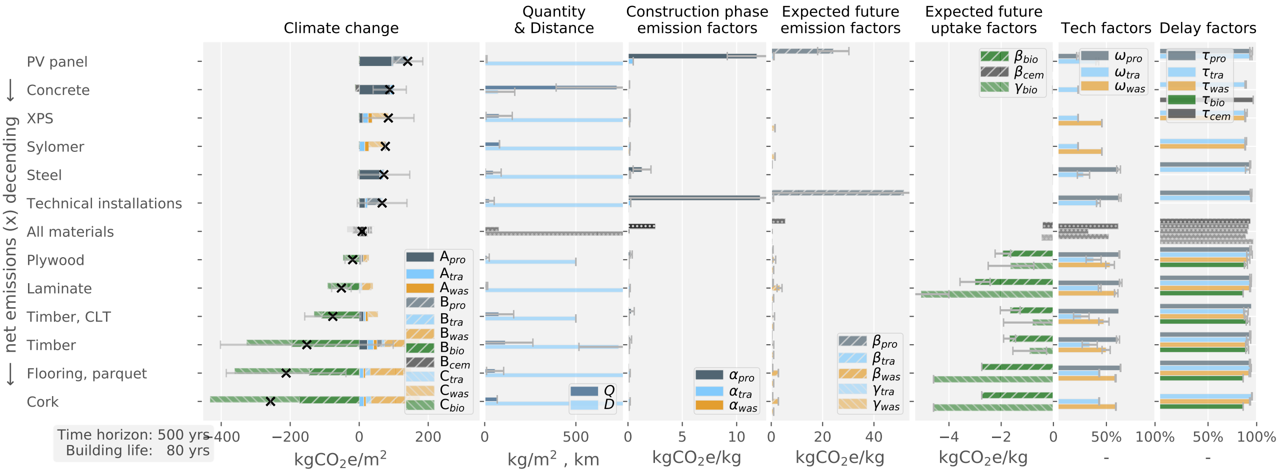

Figure E.30: 500 year time horizon.

E.4 Results for individual buildings

E.4.1 Emissions and metrics for various time horizons

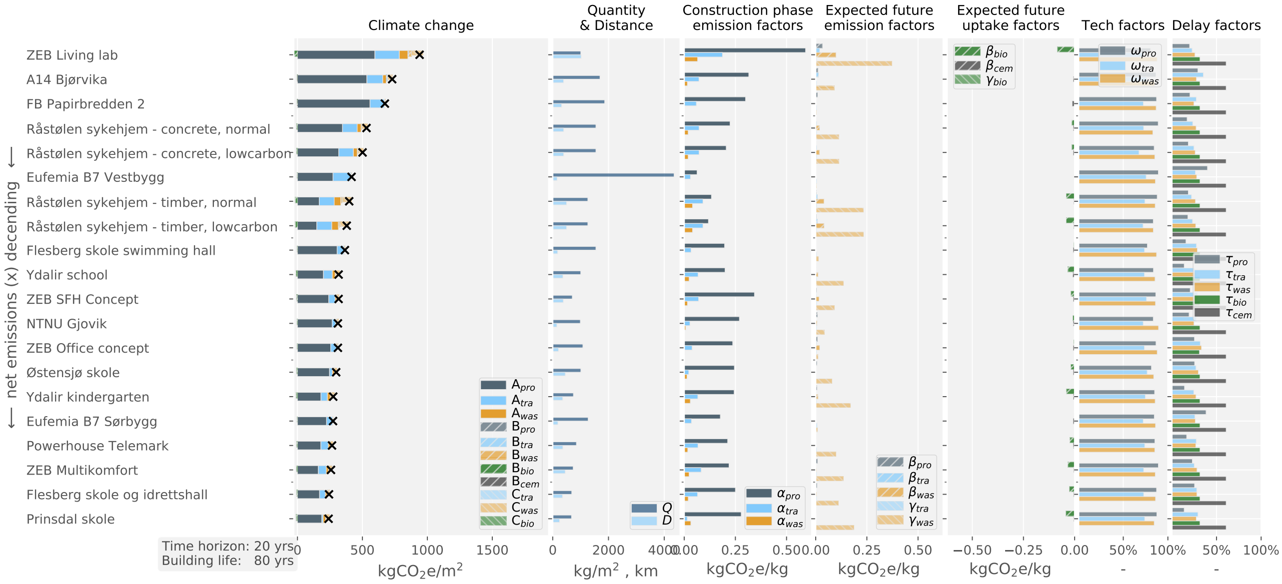

Figure E.31: Emissions and metrics of the buildings with a 20 year time horizon. Building element 2: ‘Envelope, foundation, and structure’. The metrics for the construction (A), operation (B), and end-of-life (C) phases are denoted by α, β, and γ, respectively. Future emissions and factors are shaded and hatched.

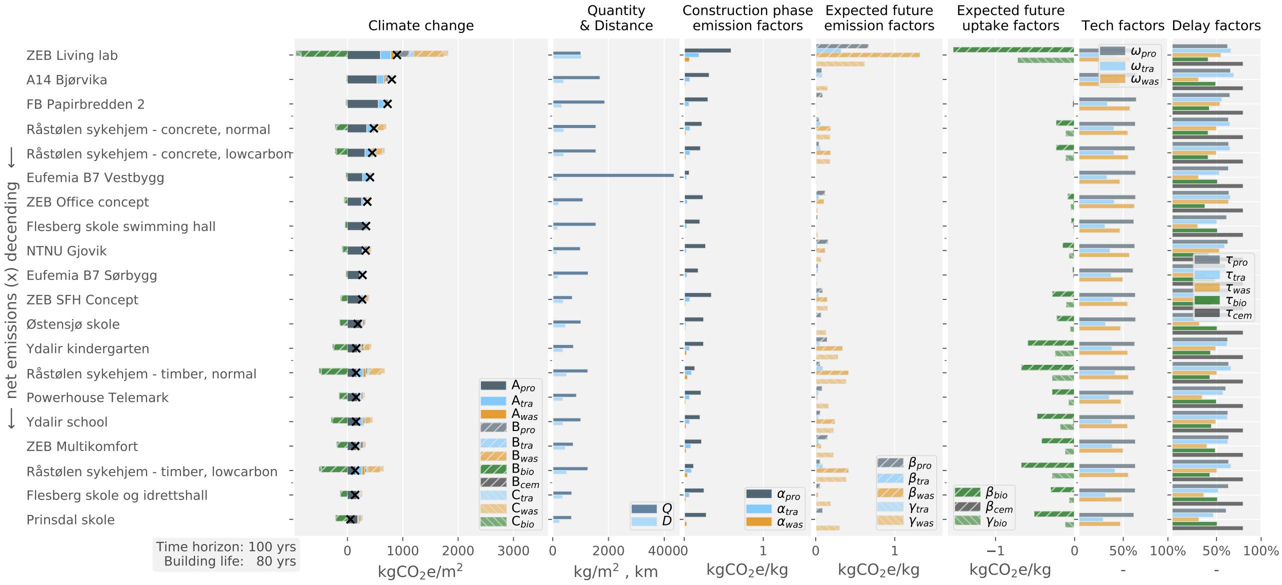

Figure E.32: Emissions and metrics of the buildings with a 100 year time horizon. Building element 2: ‘Envelope, foundation, and structure’. The metrics for the construction (A), operation (B), and end-of-life (C) phases are denoted by α, β, and γ, respectively. Future emissions and factors are shaded and hatched.

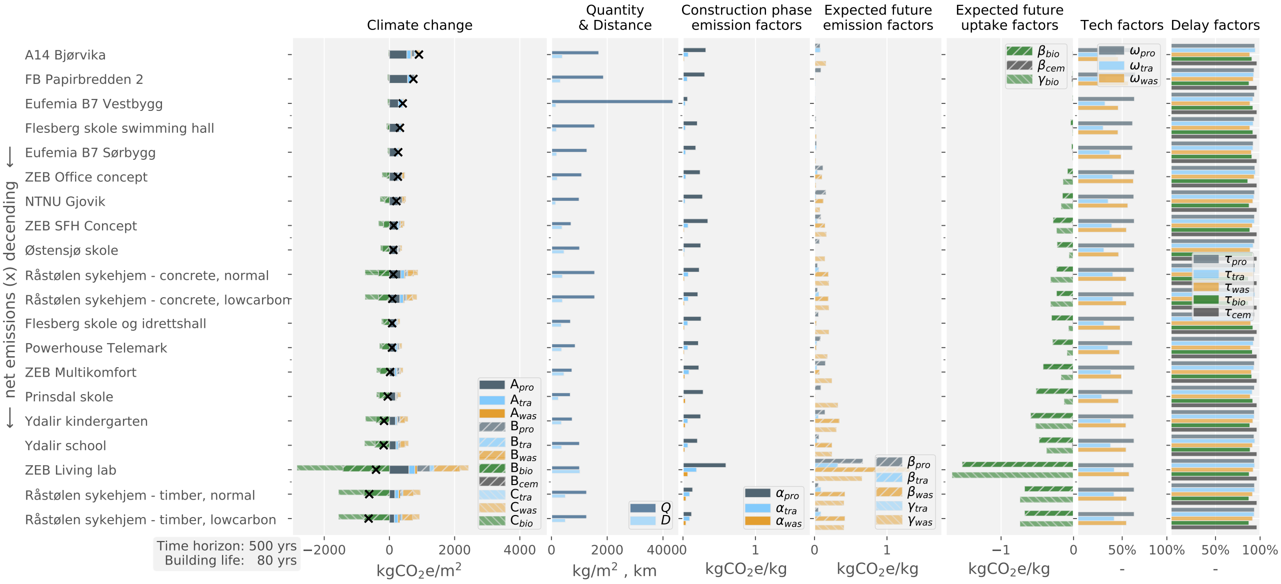

Figure E.33: Emissions and metrics of the buildings with a 500 year time horizon. Building element 2: 'Envelope, foundation, and structure'. The metrics for the construction (A), operation (B), and end-of-life (C) phases are denoted by α, β, and γ, respectively. Future emissions and factors are shaded and hatched.

E.4.2 Dynamic results for individual buildings

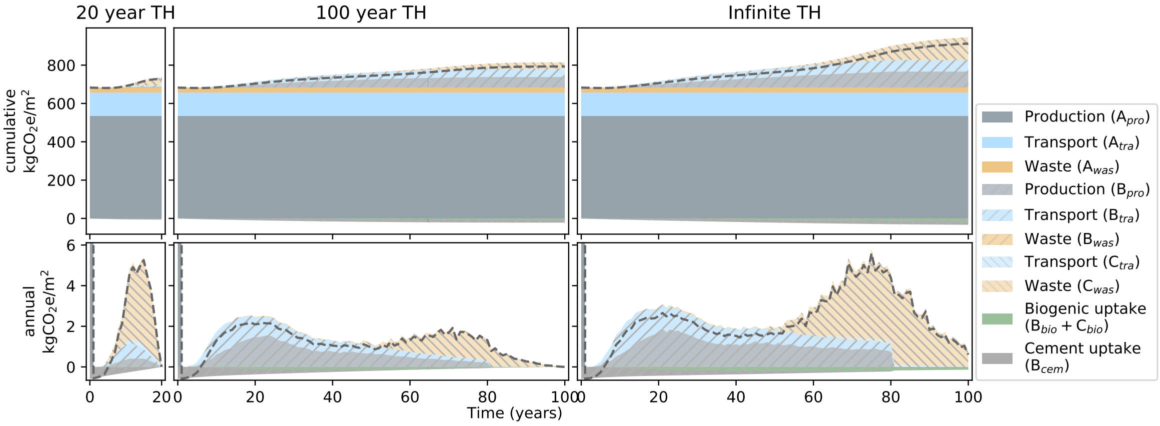

Figure E.34: A14 Bjørvika.

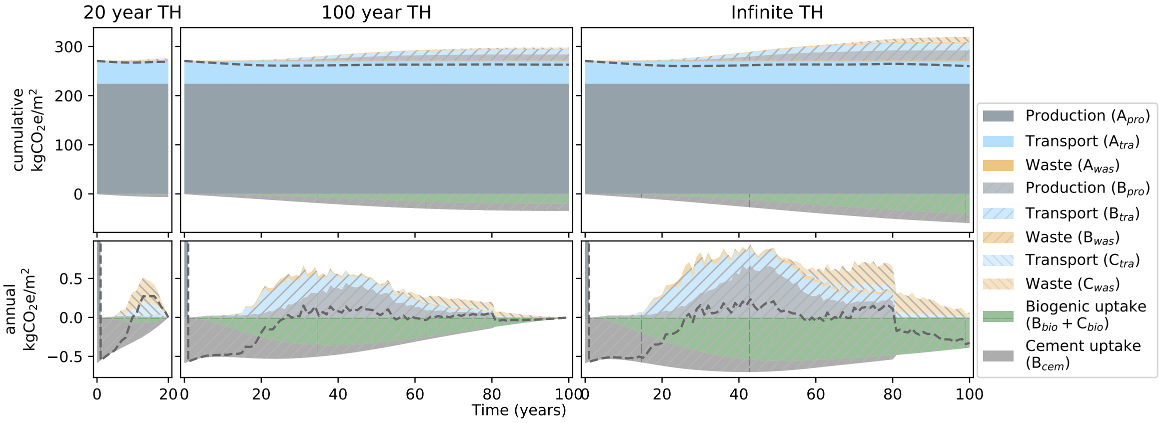

Figure E.35: Eufemia B7 Sørbygg.

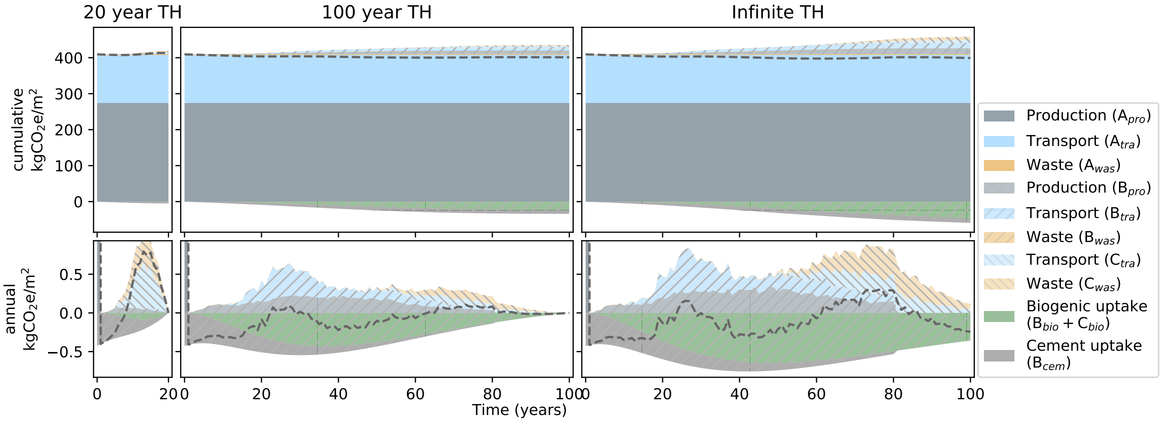

Figure E.36: Eufemia B7 Vestbygg.

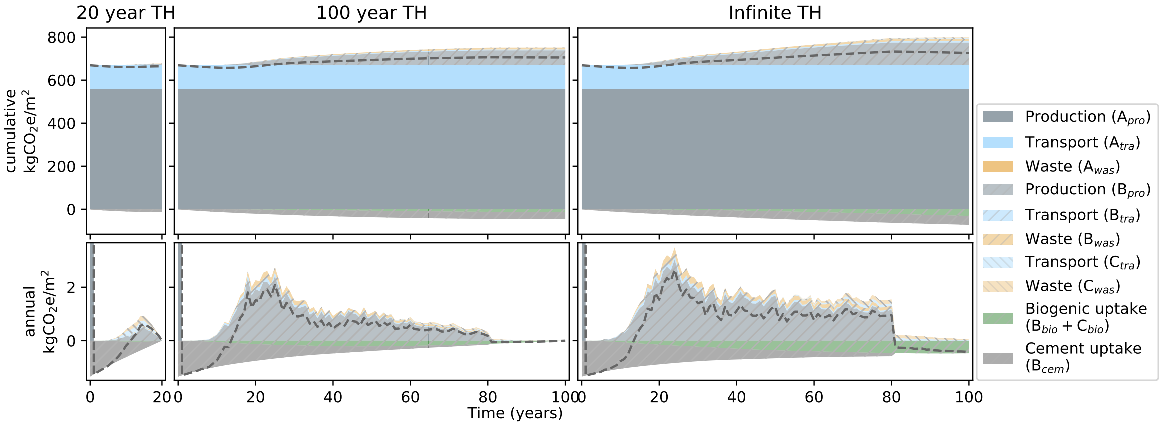

Figure E.37: Papirbredden 2.

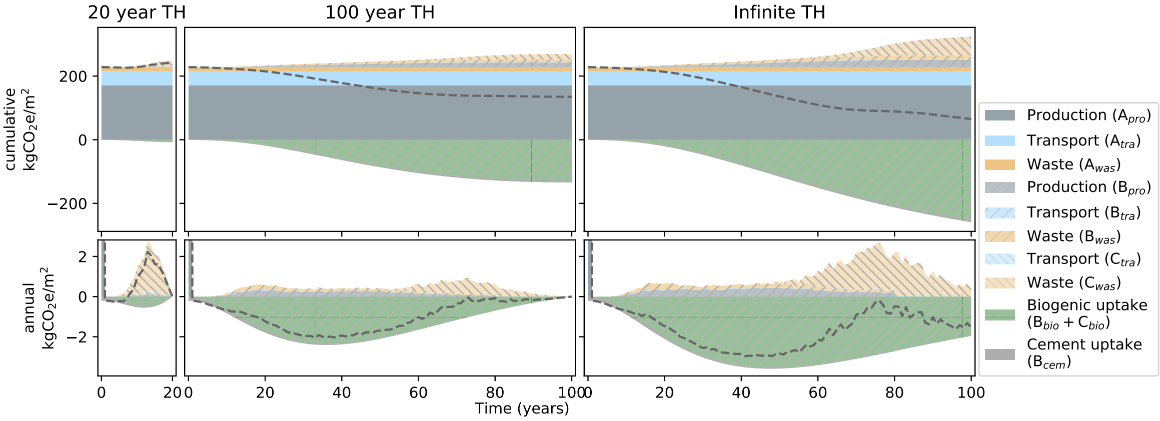

Figure E.38: Flesberg school and sports building.

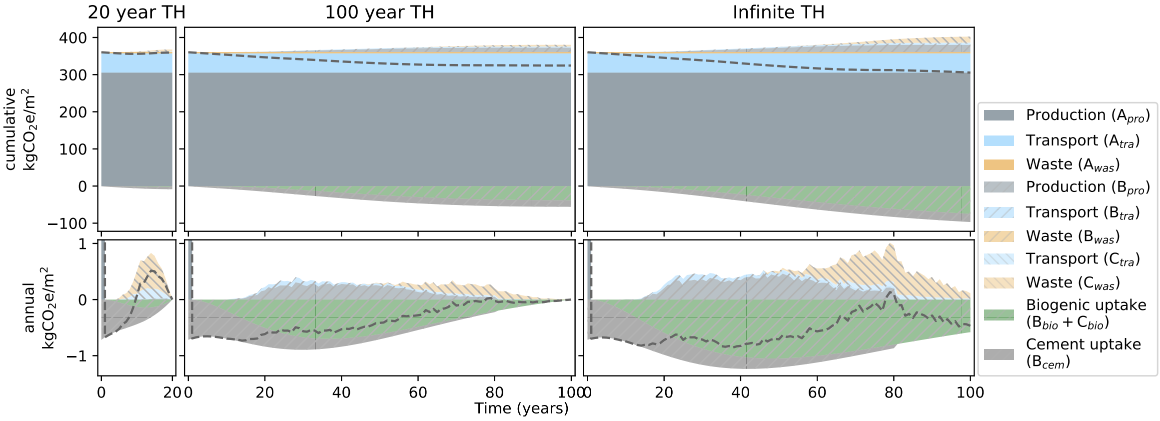

Figure E.39: Flesberg swimming hall.

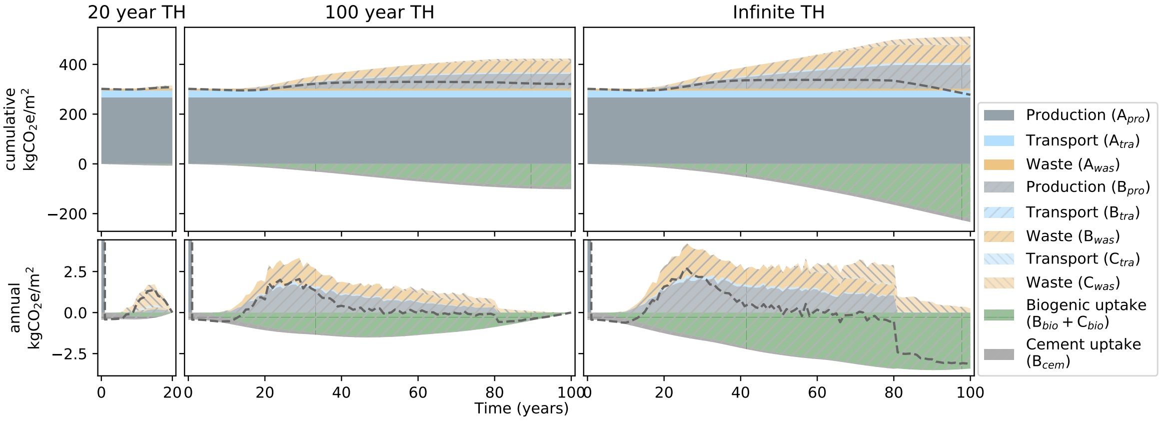

Figure E.40: NTNU Gjøvik university building.

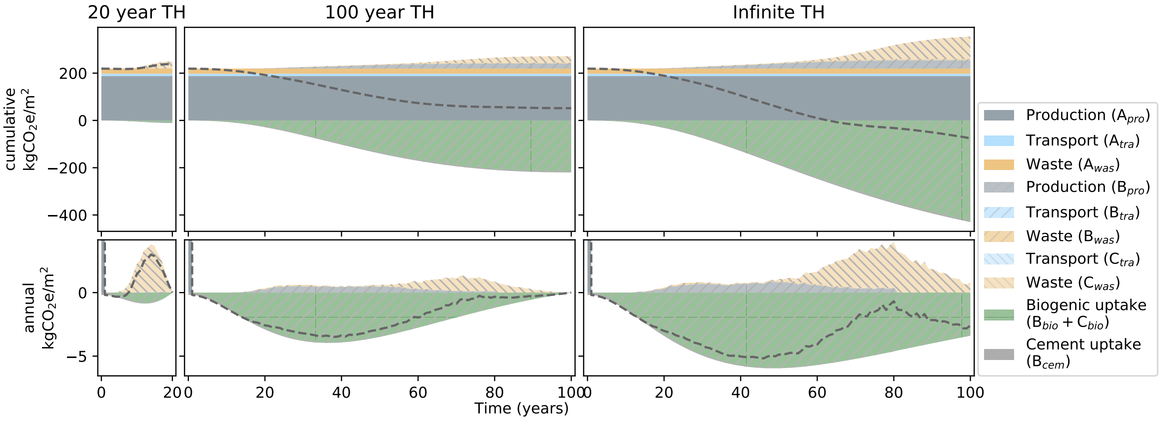

Figure E.41: Prinsdal school.

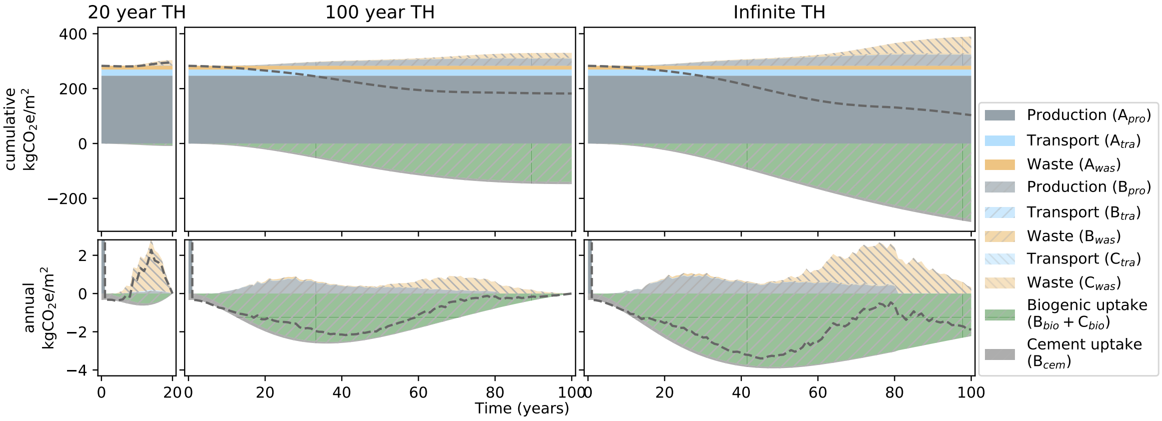

Figure E.42: Østensjø skole.

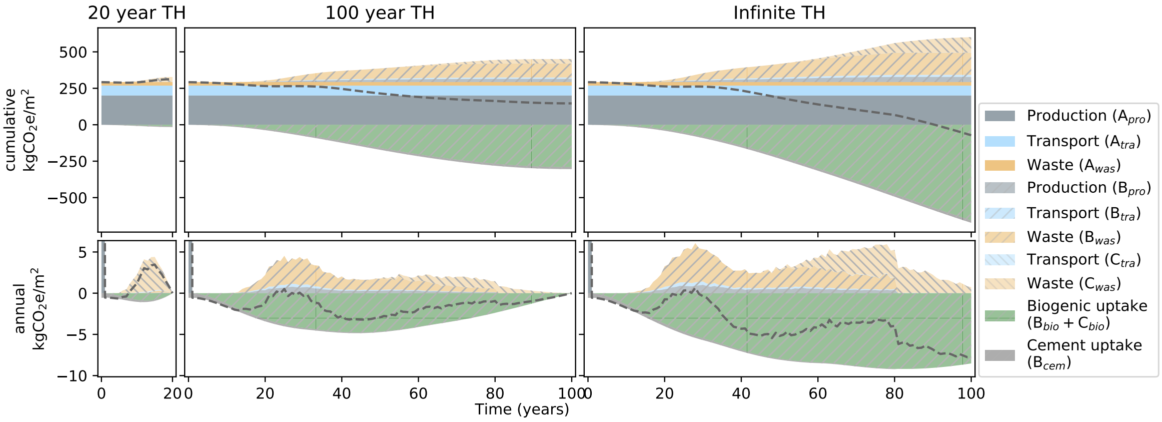

Figure E.43: Ydalir school.

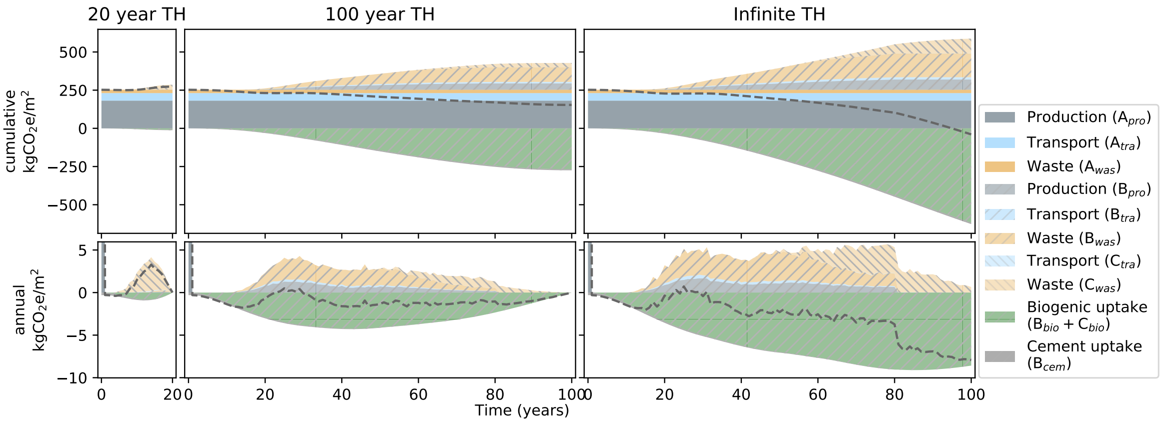

Figure E.44: Ydalir kindergarten.

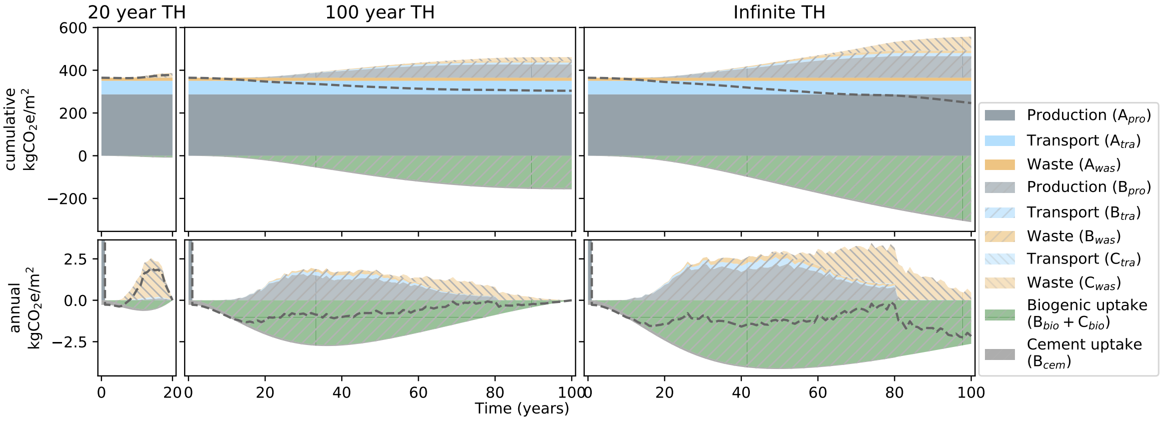

Figure E.45: Powerhouse Telemark.

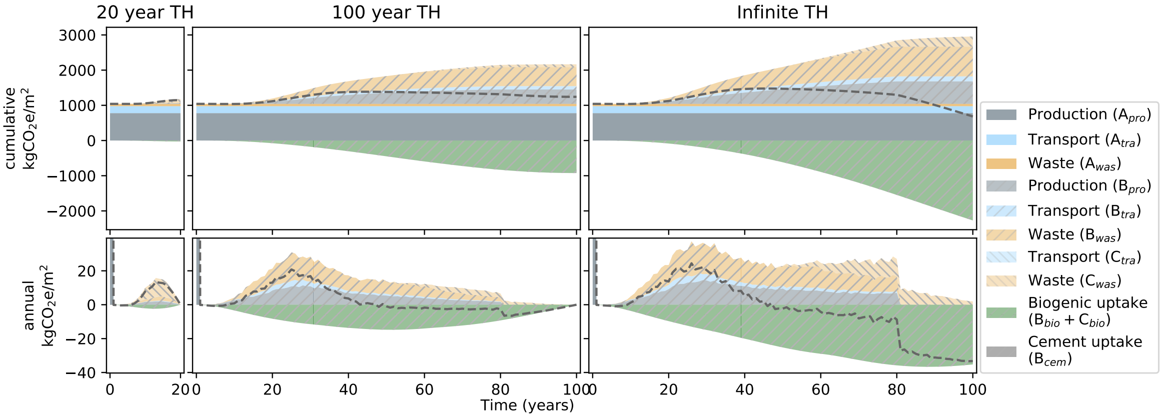

Figure E.46: ZEB Living lab.

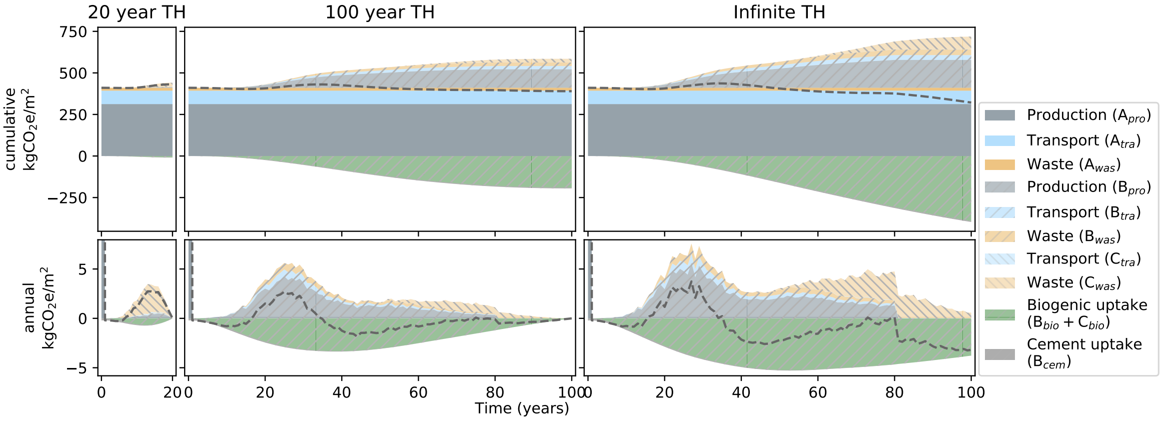

Figure E.47: ZEB Multikomfort.

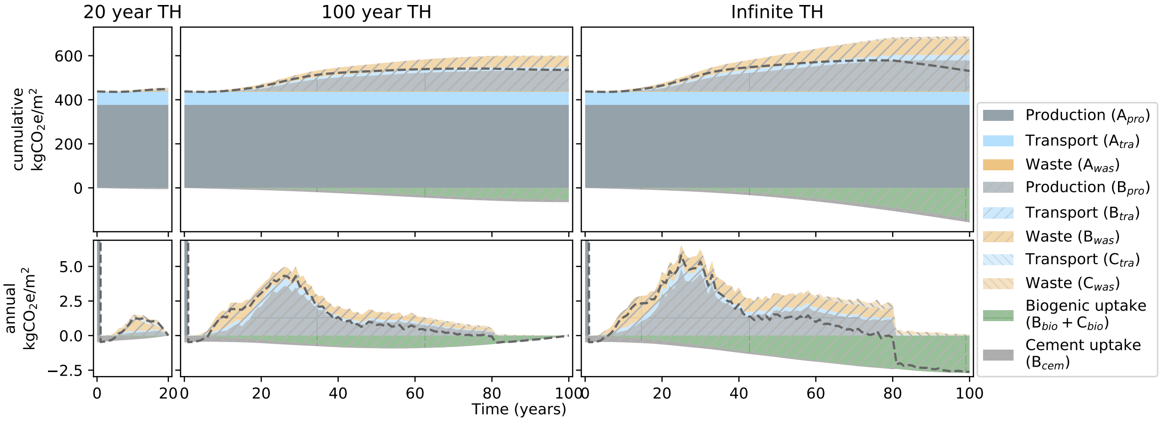

Figure E.48: ZEB Office concept.

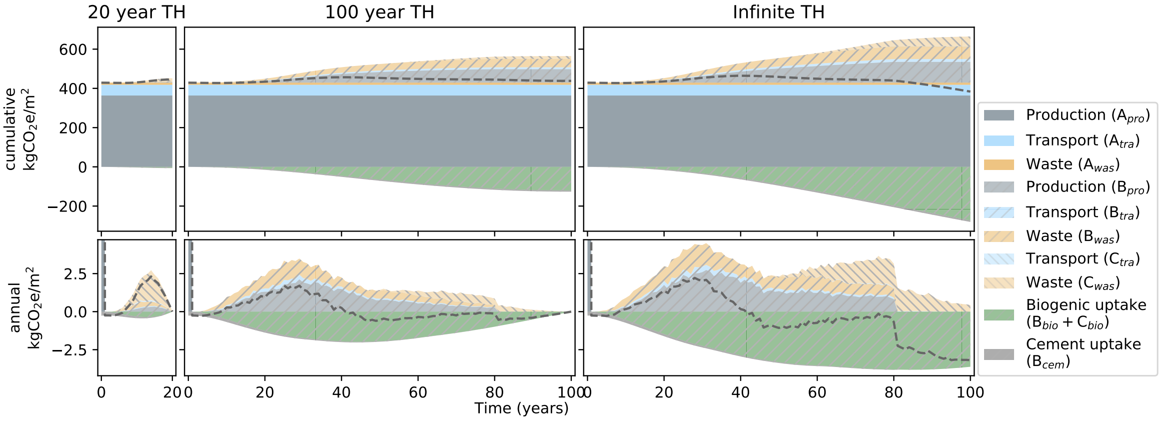

Figure E.49: ZEB SFH Concept.

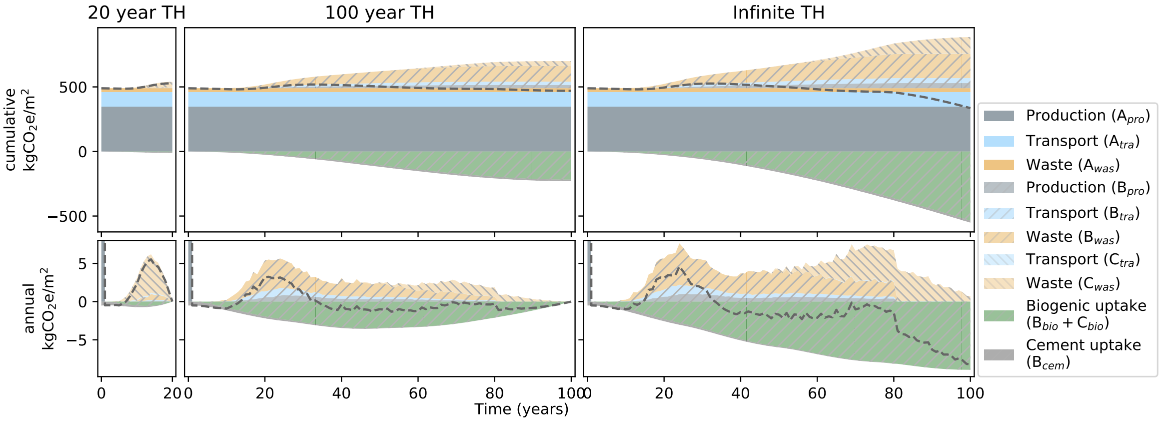

Figure E.50: Råstølen sykehjem - concrete, normal.

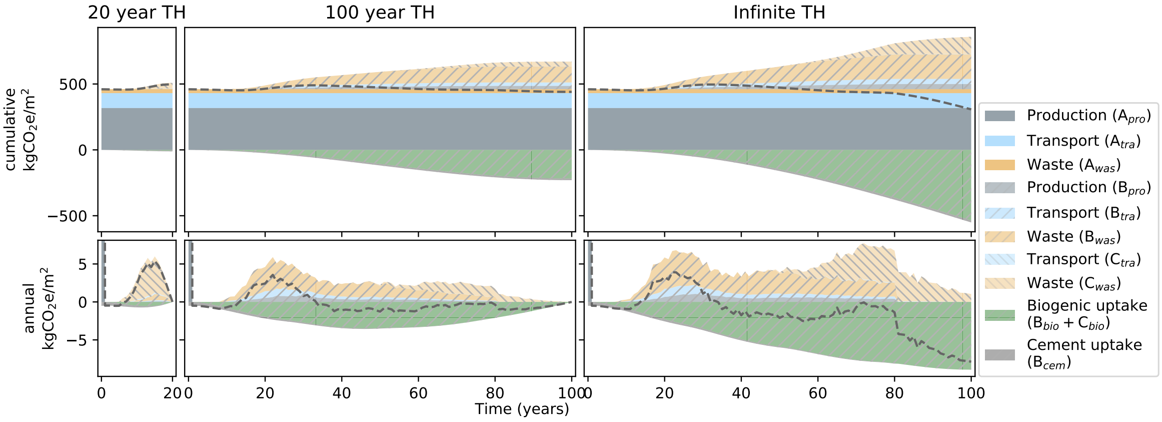

Figure E.51: Råstølen sykehjem - concrete, lowcarbon.

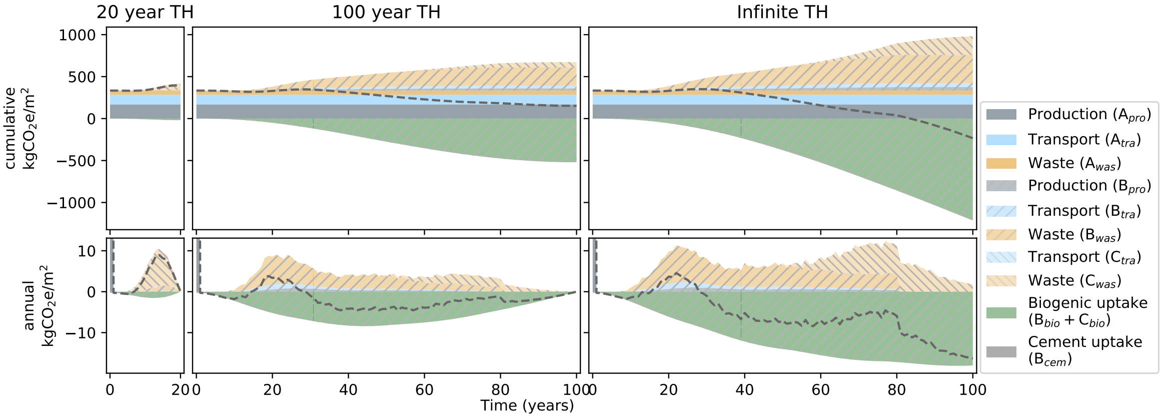

Figure E.52: Råstølen sykehjem - timber, normal concrete.

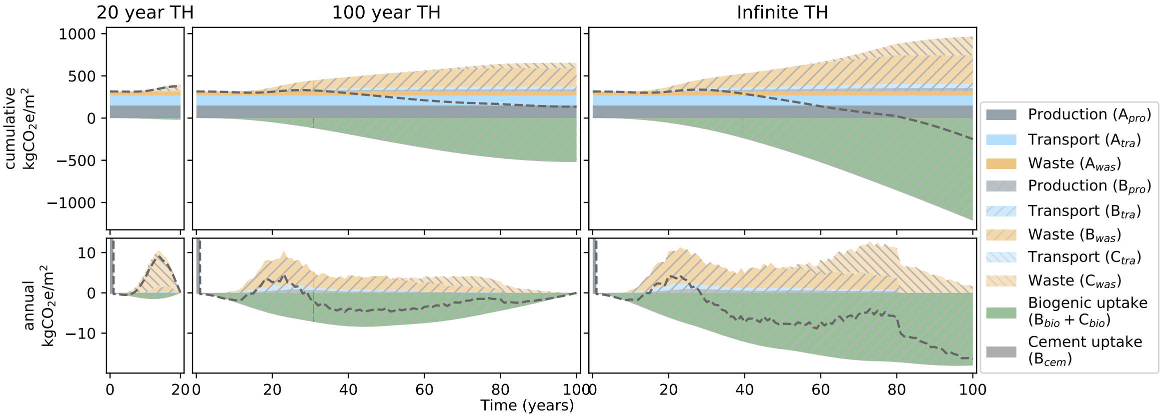

Figure E.53: Råstølen sykehjem - timber, lowcarbon concrete.

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Part C

Supplementary publications

Paper S.I

Current Challenges of Urban Energy Planning in a Norwegian Municipality

Eirik Resch, Inger Andresen

Published in the proceedings of the *World Sustainable Built Environment Conference 2017, Hong Kong*

The paper's context in the thesis:
Before deciding the focus of the Ph.D. research, this study explored the perceived needs of decision makers.

Session 7.8: Sustainable Neighbourhoods – Processes and Application

Current Challenges of Urban Energy Planning in a Norwegian Municipality

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ABSTRACT

Transitioning urban areas into sustainable communities is an important part of combating the current energy and emission challenges facing the world. The Norwegian municipality of Oslo has set ambitious energy and emission reduction goals for the coming decades. This analysis seeks to uncover how these goals are incorporated in the planning practice in the municipality.

Through in-depth semi-structured interviews with four energy planners employed in or related to this municipality's current urban development, this issue was explored. The data gathered from the interviews was analysed in relation to existing literature to reveal underlying problems, and what the potential benefits of a more integrated approach between the two planning agencies can yield.

Results from the interviews reveal that there are underlying challenges regarding system definitions, transformation of existing urban areas, making the right prioritizations, and indicate that integration between departments to reach common goals has potential for improvement. The urban planning department focuses mostly on other, non-energy related aspects of planning. From the data gathered it is clear that a stronger implementation of energy assessment in the urban planning practice can be beneficial for achieving the energy and emission reduction goals set by the municipality. New assessment methods and tools need to be developed and current tools should be stronger implemented in decision chains. Results are valuable for any government with similar challenges. As urban planning decisions will often have long-lasting implications this issue is pressing.

Keywords: *energy use, policy and regulation, design process*

1. INTRODUCTION

Cities all over the world are in the process of transitioning existing built areas into sustainable societies reducing local pollution and emissions that contribute to global warming, as set out in the Paris agreement. The goals set in this agreement, as well as the specific goals set by many local governments, are ambitious and require well-informed knowledge to identify measures that are most effective to support greenhouse gas mitigation.

The Norwegian municipality of Oslo has recently published its greenhouse gas (GHG) emission reduction goals (Oslo kommune, 2016). The overall goal is to achieve a reduction of GHG emissions of 95% by 2030 compared to 1990 levels. Achieving such an ambitious goal require dedicated integrated planning across sectors and scales, and a solid knowledge basis on which decisions can be made. The planning of cities consists on the one hand of professional objective assessments and calculations, while on the other hand there are political considerations that have to be taken into account. In energy planning, as in most areas, there is often a gap between the two. This paper seeks to identify current challenges of urban energy planning in Oslo municipality from the perspective of energy planners. Based on in-depth interviews with selected energy planners, as well as analyses of political documents and other literature, we present and discuss some of the challenges of reaching ambitious GHG emission goals.

1.1 Urban energy planning

Urban growth consists of different urban planning processes that include different aspects such as housing type and volume, traffic system, infrastructure, services, etc. The growth patterns are traditionally handled as several non-related sub-systems and processes, as opposed to a single system (Kuronen et al., 2010). Despite the high complexity of the energy sector, it can be studied in a meaningful way through an integrated assessment approach and a system-of-systems perspective (Agusdinata and DeLaurentis, 2008). Urban planning is, however, still treated as planning that considers only the spatial characteristics of a certain area (Kuronen et al., 2010), and energy planning is carried out only after the spatial plans are made. This practice is common despite that there is clear evidence of urban form affecting energy use (Weisz and Steinberger, 2010). An inter-organizational structure is argued by Korhonen (2004) to be an important element in successful urban planning, but is traditionally not part of the process, resulting in environmental management not being handled with a systems understanding. In a review paper (Keirstead et al., 2012), six approaches to urban energy system modeling were identified; technology design, building design, urban climate, system design, policy assessment, and integrated land-use and transportation. They conclude that “there is significant potential for urban energy systems modeling to move beyond single disciplinary approaches towards a sophisticated integrated perspective that more fully captures the theoretical intricacy of urban energy systems”.

1.2 Greenhouse gas accounting and system boundaries

Transitioning to zero-emission cities requires an increase in energy efficiency (reduction in consumption) and a shift to renewable energy sources, for all of the city’s activities. These activities include energy generation and energy use, as well as considering the import and export of goods that have associated emissions from their production and transportation. The energy consumption includes energy use for industry, transport, and buildings. Energy generation happens both within and outside of the municipalities’, and energy may therefore be imported or exported across the borders of the municipality, thus representing credit or debit in the CO_2-account of the municipality. The imported and exported goods are hard to account for and are therefore normally not taken into account in cities’ emissions accounting.

Renewable electricity from hydropower is abundant in Norway, and associated emissions from electricity production are small. Norway produces a surplus of electrical hydropower in a normal year. However, electricity is exported and imported with the European market and the actual electricity mix is, therefore, a more complex issue; what the marginal emissions are per kWh is a topic under discussion (Graabak et al., 2014). The municipality of Oslo has chosen not to allocate any emissions to the use of electricity from the grid. Within this definition, the used electricity is therefore not seen as a problem, but rather the remaining activities such as transportation, industry, waste generation and district heating plants. Still, the municipality has a focus on energy efficiency related to electricity use. The reason expressed for this is that it will “free up” electricity for other purposes such as electric vehicles and energy-intensive industries, as well as “be made available for export to other countries”. In addition, there are economic benefits of energy efficiency. Energy efficiency is in this way used as a proxy for reduction of greenhouse gas (GHG) emissions, but at the same time, there are by definition no emissions associated with it. The Climate- and Energy Strategy of Oslo is, therefore, twofold; an increase in energy efficiency and a reduction of direct emissions within the municipal borders. When assessing GHG emissions it is vital to set the system boundaries defining what to account for and what to exclude from the calculations. The system boundary definition will decide which actions will be taken to move towards the goals.

1.3 Political guidelines

The Climate- and Energy Strategy for Oslo municipality (Oslo kommune, 2016) was approved by the city council in June 2016. The overarching goal is a 50% reduction in GHG emission by 2020, and a 95% reduction by 2030, compared to 1990-levels. There are 16 target areas, whereof 10 are directly concerning emission reductions, and 4 are concerning the municipality’s governance towards emission reductions. The remaining two target areas encompass energy efficiency in buildings and water-based heating and cooling systems.

The Norwegian Planning and Building Act is the legal binding document for planning and building permits in Norway. In addition to this, there are national guidelines that supplement and elaborate on expectations from the national level to the local. The Norwegian Ministry of Local Government and Modernization have national guidelines on Integrated Residential-, Land-use-, and Transport planning released in 2014 (Ministry of Local Government and Modernisation, 2014). The guidelines seek to promote better resource efficiency and the development of sustainable cities and communities through compact urban development coupled with sustainable modes of transportation. Also, they state that the development of new residential areas should be evaluated together with the need for infrastructure. Similar goals are stated in the Climate- and Energy Strategy.

2. METHODS

The empirical basis of the paper is based on three in-depth semi-structured interviews. In one of the interviews there were two interviewees, and in the two remaining there was one, thus in total, four persons were interviewed. The informants were specifically selected based on their central roles in the energy planning and the Climate and Energy Strategy of Oslo municipality. The interviews took place in the offices of the informants or at the university and lasted approximately one and a half hours each. An interview guide was adapted for each interview. The interviews were recorded and transcribed. When analysing the interviews, a phenomenological approach was chosen, with a focus on the interpretation of the expressed statements in the context of the planning literature, the political goals and guidelines and the GHG emission accounting systems described in Section 1. The interviews were first read and highlighted, then, information was extracted, categorized, and compared. Finally, the findings from the interviews were analysed in the context of the issues outlined in Section 1.

3. RESULTS

The interviews revealed some challenges that were experienced by all informants as well as some that were pointed out by some interviewees. This section includes a synthesis of the content as expressed by the interviewees as well as descriptions of underlying challenges that were discovered.

3.1 Challenges in transforming existing built areas

The informants pointed out the special challenges of transforming existing areas. Different reasons were given to explain this; zoning restrictions; inhabitants' unwillingness to make changes, and long payback times for investments in the upgrade of buildings and energy infrastructure. They voiced the need for planning instruments for application in already existing areas, especially to tackle problems associated with the structure of ownership.

Oslo has a goal of densification, and to achieve a compact mixed-use urban environment. This goal was described as challenging to reach in some parts of the city due to active resistance from the people living in the area, which significantly slows the rate of densification. In these areas, there is strong resistance to building both taller than and close to existing houses.

3.2 Poor integration between energy planning and land-use planning

Although the integration between energy planning and land-use planning has been agreed upon and stated in documents, the integration has not been transferred into practice. However, the interviewees note that there is an increasing focus on this issue, but the practical implications are still very subtle. The integration mainly takes place in the form of interdisciplinary working groups and meetings. Still, the experience of some of the interviewees is that land-use planning is happening almost completely separate from energy planning. During land-use planning, all other concerns, such as the contractor's desire for profit, the municipality's concerns for good urban development, roads, and infrastructure, are prioritized. Energy planning is mainly done by the utility companies, and only after the zoning plans are set by the municipality.

Integrating transportation and land-use planning is considered very important, and to be the main tool available to the municipality for reducing transportation-related energy. On the other hand, the importance of focusing on energy efficiency of stationary energy use in land-use planning is questioned by some, but at the same time encouraged and wished for. Building close to public transportation hubs together with increased density and strict building energy codes are considered to be more important. On a stronger inter-organizational planning structure, opinions were mixed; both open to future reorganizations, and an emphasis on the need for dividing areas of responsibility.

3.3 Comparing the incomparable and the need for a common understanding of greenhouse gas emissions

A central problem mentioned by all interviewees was the challenge of comparing the incomparable. This can be synthesised in the following way: "We don't have the common underlying understanding and agreed upon framework for comparing different options in the right way". Since there are many variables affecting energy use, it was considered hard to assess impacts of different options. It was also expressed as a concern that there is not a common agreed upon framework for greenhouse gas emission accounting. This is related to the setting of system boundaries; that setting different boundaries will either lead to emissions not being counted, being counted differently, or that the emissions are shifted. It was voiced that this can put a specific energy solution in a negative light, disfavouring its use and that it might also lead to overall wrong prioritization on the municipal level.

There was no disagreement about the choice of not attributing any emissions to waste incineration in the district heating system. It was reasoned that the emissions are allocated to the waste sector which means that they are included elsewhere in the calculations. Also, it was argued that the waste handling system in Oslo was considered to be “particularly good”, and further improvements are planned. The heat from incineration is therefore considered to be waste heat. It was, however, pointed out by one interviewee that defining district heating as 100% renewable makes it hard for other options to compete, and in some cases, it might lead to a suboptimal solution being chosen.

Three informants described a concern that central energy solutions are disfavoured due to the way energy use in buildings is accounted. District heating solutions are said to be disfavoured in some cases because it is defined as delivered energy rather than primary energy, while delivered energy is what is taken into consideration in calculations. An example used was that local heat pump systems are often preferred over central heat pump systems due to the system boundary of delivered energy.

The fact that electricity had been defined by the municipality as having zero emissions was set forward as a more difficult topic. One of the interviewees particularly considered this to be a central problem, explaining that a consequence of such a definition is that there are no incentives for reducing electricity consumption to reduce emissions. There are two separate goals being promoted, one is energy efficiency and the other is emissions reduction. Although an underlying motivation for energy efficiency is the reduction of emissions, it is not counted as such by the municipalities. In this framework, they are incomparable, and improving one of them will not have any effect on the other. For instance, substantial subsidies are given for installing PV panels, when in fact, it is not helping the municipality to get any closer to the emission reduction goal. It was said that if the goal of improving energy efficiency is to reduce emissions, then the framework is not right. The interviewee argued that since the electricity from hydropower is part of the Nordic and European markets, a carbon component that is related to the actual electricity mix is needed. It was noted that the exact component related to a marginal use might not be possible to calculate, but there is a need for discussion of the principles on which this definition is made, which may lead to more well-informed incentives.

When being asked about what tools and assessment methods that could support a more holistic planning in the municipality, one of the interviewees expressed that, although such tools are welcomed and needed, there were doubts about the feasibility of creating them. Moreover, the belief in the benefits of such tools were limited. The opinion was that it is not hard to agree on the basic principles for an environmentally friendly city, such as mixed-use areas that have most services within 5-10 minutes of walking distance, placing housing close to public transport infrastructure, making electrical vehicles attractive, and strict building energy codes. Together, it was said, they will result in an energy efficient, climate-friendly city, and to calculate and quantify the effects can be demanding. Even if it is possible, it was questioned whether such calculations are necessary.

3.4 Prioritizations of actions made on insufficient basis

There was a concern that there is not a good basis on which important decisions on prioritization of resources are being made, expressed by one informant, saying that we are not doing enough cold, “cynical”, objective evaluations on what measures will be important in reaching the goals. It was stated that choices are too often made to promote spectacular, visible lighthouses and that there is too little focus on what actually has an effect. Examples of this included the willingness to support research and infrastructure for hydrogen, and the subsidies on PV panels; both of these measures not being coupled to the GHG emission reductions set by the municipality’s definition. It was reasoned that when the municipality is setting such bold goals, money should be more deliberately spent on reaching those goals.

4. DISCUSSION

The scope defined by the municipalities will have a big effect on the outcome of GHG emissions accounting, and can to a large extent determine where the focus is put on energy and emissions reductions. Since Oslo is not allocating any emissions to the electricity or waste incineration in district heating, there is a danger of not putting enough effort into reducing emissions from these sources, and thus encouraging consumption of these. Oslo municipality argues that they do focus on both energy efficiency in buildings, decreasing energy consumption from heating (mostly based on electricity and district heating), and on reducing emissions from the district heating facility. These goals are also clearly stated in their Climate- and Energy Strategy. This reveals that the municipality has a systems view on their sustainability approach that surpasses their emissions accounting. Nevertheless, a contradiction arises when two of the target areas by the municipality's definition are not related to GHG emission reduction, but rather on energy efficiency in buildings and water-based heating and cooling systems. Fossil fuels are being phased out from these two areas, which will soon render them emission free by this definition. We argue that there is an inconsistency in the municipality's reasoning, in that both electricity and waste incineration in district heating are considered to be emission-free, while at the same time energy use for heating and cooling in buildings is given high priority. It is possible that having two separate goals, achieving higher energy efficiency and reducing emissions, might not be the best way of mitigating climate change. By using a conversion factor between electricity demand and emissions, such as the ones described in Graabak et al. (2014), the GHG reduction potential of reduced energy use can be compared with other GHG reduction efforts to assure that each area receives the prioritization that will have the most effect on emission reduction. We should, therefore, have a scientific basis for the effect of these measures, and align our goals and actions thereafter.

When building district heating infrastructure based on the assumption that it is utilizing waste heat to recover energy, one should be careful that the infrastructure dependence on district heating does not make the municipality dependent on having a supply of waste beyond that which can be expected in the future. Especially since the municipality has a goal of reducing upstream waste, the future impacts of these two possibly conflicting efforts should be considered. An analogy can be drawn from research showing that there is a far greater benefit in reducing food waste than in recycling it for energy recovery (Hamilton et al., 2015).

In the interviews, it became clear that energy planning follows after land-use plans are developed. This is consistent with Kuronen et al. (2010) and signifies improvement potential in a stronger integration of the two sectors (Korhonen, 2004). Efforts in the municipality should thus be continued in this area. Stronger inter-organizational integration could also be considered, as argued by Korhonen (2004).

A concern was expressed in the interviews regarding the importance of achieving, and the feasibility of achieving, an integrated model for urban energy planning and land-use planning. Although the difficulties of isolating variables and creating such a model are documented in literature (Weisz and Steinberger, 2010), as described in Section 1, integrated assessment has proven successful despite the complexity of the energy sector (Agusdinata and DeLaurentis, 2008). While there is still a need for improvement of models, there is significant potential for urban energy systems modeling to move from single disciplinary approaches to a sophisticated integrated perspective (Keirstead et al., 2012). Quantifying to what extent different measures are successful can lead to the formation of more effective strategies.

The difficulty in transforming existing built areas is a barrier to reducing transport, renewing energy solutions, and altering urban form. There is thus a need for planning tools that reduce the challenges associated with this transformation.

We do not argue that cities should be planned only according to energy and emission reduction, but that a large fraction of the planning process can be done in this way, and that it is possible to make better quantitative integrated solutions than the ones used for the decisions taken today in the planning practice.

5. CONCLUSION

From the interviews, it was found that there are some underlying challenges and areas of conflict that materialize as hindrances to reaching the goals set by the municipality. The energy planners find it hard to achieve the goal of a zero-emission city without a clear framework for evaluating alternatives and a holistic calculation tool for determining the effects of policy choices. There is thus the need for the development of such a tool and a scientific discussion on how to evaluate alternatives in a holistic way.

This research is part of a work to map the needs of municipalities in the transition to sustainable cities. The work will continue in other municipalities. Thereafter, based on the results we will develop methods and tools that will tackle the obstacles discovered.

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Paper S.II

The role of utility companies in municipal planning of smart energy communities

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The paper's context in the thesis:
The paper builds an argument for a clear need for definitions and strategies that can strengthen the role that municipals must take to manage planning towards a zero-emission vision.

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THE ROLE OF UTILITY COMPANIES IN MUNICIPAL PLANNING OF SMART ENERGY COMMUNITIES

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ABSTRACT

Bergen and Oslo municipalities focus on integrating energy concerns into city planning and regard this as an opportunity to further lower greenhouse gas emissions. Due to a lack of tools and clear definitions of what Smart Energy Communities (SECs) are and how planning should be done in order to affect the overarching emission reduction goals, utility companies end up taking a leading role as advisors and influence definitions and strategies in the final design. Based on two case studies of SEC projects in Norway, the authors highlight the need for increased work to create feasible and understandable definitions and strategies for the planning of SECs. In our case studies, city planners struggle to include energy aspects in the early planning phase and to align their objectives of citizen well-being and reduced private car dependency with energy concerns. At the same time, utility companies respond to the perceived threat of more self-sufficient communities by depicting a role closer to the end-user and by offering a pragmatic cost/benefit view on the planning of energy supply options.

Keywords: Energy planning, Integrated energy planning, Smart Energy Communities, Sustainable urban planning, Zero Emission Neighbourhoods

1 INTRODUCTION

This work is part of an ongoing national research project entitled Planning Instruments for Smart Energy Communities (PI-SEC) that aims to deliver efficient planning instruments for integrated energy design at the neighbourhood scale, qualified for Norwegian planning context in cooperation with public stakeholders.

Smart Energy Communities (SEC) and Zero Emission Neigbourhoods (ZEN) have no agreed upon definitions. For buildings, researchers have attempted to define zero or near zero emission/energy levels [1–3] based on different cases and target achievement in different countries. Finding a common ground on what defines zero emission communities and neighbourhoods becomes even more challenging. The complexity of this question, together with the current efforts to integrate energy aspects into urban planning, means that multiple stakeholders, including utility companies, private developers, municipal planners, and politicians have the opportunity to influence the definitions of SEC and ZEN when planning new communities and neighbourhoods. Our working definition of SEC is 'an area of buildings; infrastructure and citizens sharing planned societal services, where environmental targets are reached through integration of energy aspects into planning and implementation. The Smart Energy Community aims to become highly energy efficient and increasingly powered by renewable and local energy sources and lowered dependency on fossil fuels. The spatial planning and localization of the SEC targets reduction of carbon emissions through the relationship with the larger region, both through the design of energy systems and by including sustainable mobility aspects of the larger region. It further encourages sustainable behaviour through its overall design from building and citizen scale to community scale'. Societal services is here meant as in the sequence of order common in Norway's planning and building act; such as energy delivery, transportation and road network, health and social services, kindergartens, play areas, and schools.

Norway has committed to ambitious targets for reduction of greenhouse gas emissions (https://www.regjeringen.no/en/topics/climate-and-environment/climate/

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innsiktsartikler-klima/agreement-on-climate-policy/id2076645/). Two municipalities, Bergen and Oslo, have taken lead roles in reducing their greenhouse gas emissions. Bergen has stated that they will be 'Norway's greenest city' by becoming a '1.5-degree city [4]', while Oslo aims to reduce emissions by 50% within 2020 and 95% within 2020 compared to 1990 levels [5].

In the presented study, we analyse and compare the planning of two Norwegian SECs through interview analyses. The planning of Zero Village Bergen (ZVB) and Furuset Forbildeprosjekt materialize Oslo and Bergen municipalities' ambitions to integrate energy into spatial planning. ZVB is a planned and designed development project, which is to include approximately 800 new dwellings, a kindergarten, and some commercial buildings in an uninhabited area north of the city of Bergen. This project is ready to be implemented yet still awaiting final political approval. Furuset Forbildeprosjekt is a re-development project to be integrated into an existing neighbourhood within the city of Oslo. It includes 2500 planned new dwellings in the city area and aims to create 1500 new workplaces. Parts of the plan have been implemented; including a park to improve the social aspects of the area.

The challenges of cross-disciplinary tasks such as the integration of energy into urban planning are described as being wide reaching and complex. This is explained in literature on utility management describing political challenges and stakeholder collaboration [8, 9]. Historically, we know that the Norwegian energy sector has been closely related to the political level of building policy because the energy sector has been governed by the state. The energy sector in Norway was state run but underwent the same liberalization of utilities as elsewhere in Europe during the 90s [10, 11]. There are some studies describing the influence of liberalization on urban governance and energy planning [12–14]. These studies describe that municipalities went from having a clear decision-making role in energy planning to having a negotiation role seeking to involve utilities in their planning processes. After liberalization took place, municipalities had to invest more time and effort into collaboration, which means that they have a need for negotiation skills and suitable collaboration methods. We assume that Norwegian municipalities currently find themselves in this negotiating role with utility companies, as we see that the municipalities attempt to integrate energy aspects into urban planning.

Based on a study of two Smart Energy Community cases we want to add to the described literature and to the emerging knowledge on the integration of energy in urban planning by investigating the role of utility companies in the planning of SECs. By integrated energy planning we mean 'an approach to find environmentally friendly, institutionally sound, socially acceptable and cost-effective solutions of the best mix of energy supply and demand options for a defined area to support long-term regional sustainable development. It is a transparent and participatory planning process, an opportunity for planners to present complex, uncertain issues in a structured, holistic and transparent way, for interested parties to review, understand and support the planning decisions' [16].

During our analysis of interviews with city planners, climate sections in the municipalities of Oslo and Bergen, and with representatives of the involved utility companies, we found that the issue of energy competency within the municipalities composes a significant challenge when moving towards integrated energy planning. Within this paper, we seek to discuss and answer the following three research questions:

a. What is the utility companies' role in shaping definitions and strategies in the planning of SEC (based on the two case studies)?
b. How do utility companies see their future role in integrated urban energy planning?
c. Which measures may be taken within municipal planning of SECs to help manage the identified challenges and opportunities?

2 METHODOLOGY

Between June and October 2016, we conducted 15 semi-structured interviews with involved stakeholder participants in two Smart Energy Community (SEC) projects in Oslo and Bergen respectively. Four interviews were conducted with utility companies, six with municipal planners, three with researchers from NTNU and Christian Michelsen Research, one with the coordinating organization Futurebuilt, and one with an architectural company central to the ZVB project. FutureBuilt is a ten-year programme (2010–2020) with a vision of developing carbon neutral urban areas and high-quality architecture. The interviews were done in person and lasted between 45 and 60 minutes. The interviews focused on taking a narrative approach combined with graphic elicitation [17, 18]. A narrative approach means that the interviewer seeks to achieve a chronological account from the participants' perspective of something. In this case, we wanted to understand each participants' experience of the planning process of these SECs. The graphic elicitation [17, 18] part implied that we asked the participants to draw a diagram, which represented a timeline of the planning process. During the drawing exercise, we asked the participants to think aloud and explain which factors had influenced the process and the outcome. This method improves the understanding between the interviewer and the interviewee, and assists the communication process. Participants were selected following a selective snowball approach [19]. This means that we had a primary sampling requirement that the participants needed to have been involved in the SEC planning; next, that it was a chain of referral that guided the sampling. We started with the project leader who had the most information about the entirety of the planning timeline and then interviewed participants following suggestions from the first participant. This approach made it possible for us to compare the different views by their explanation of the timeline and which challenges and solutions had occurred, as well as insights into who and what were keys to solving the said challenges. Following this task, we asked how the participants defined Smart Energy Communities (SEC) and Zero Emission Neighbourhoods (ZEN), and which challenges they regarded as contextual challenges of the planning of the two cases. By contextual we mean site-specific, but we also explained that we were interested in views on regional or national characteristics that might make SEC planning different compared to other countries. We transcribed the interviews verbatim and analysed them to find meaning bearers that could provide insights into how participants define SEC and ZEN, as well as what are the challenges to achieve these goals/visions, and what is the current and future role of the utility companies

3 FINDINGS

We present our findings in the same sequence as the three research questions.

3.1 What is the utility companies' role in shaping definitions and strategies in SEC development (based on the two case studies)?

As explained in the methodology section, we asked the involved stakeholders in each project to draw a timeline indicating the different steps of the planning process. They explained when and why different stakeholders were involved as well as the main challenges and strategies. We learned that the major utility companies had come on board about 2/3rds into the planning process in both projects, after the sites had been selected and the zoning plan had been designed. Once the utility companies were onboard, however, it seems as if their influence on the project quickly increased, as the projects were getting closer to implementation and into the implementation phase. It is not clear-cut to say which parts of the timeline should be defined as “planning” or when it transitions to ‘implementation’, yet we still perceive both of the projects to be in the late planning phase as they are still awaiting political approval and are discussing relevant design issues. In the Oslo case, the planning process involved mainly city planners in dialogue with citizens and included urban design competitions to meet expectations of citizens. In the ZVB case, the early planning involved researchers from NTNU and CMI, the architectural office Snøhetta and the energy consultant Multiconsult, together with the private developer. The two projects have well-defined goals in terms of emission reduction. Yet, it appeared that the utility companies viewed the projects in relation to their overall market approach within the concession area and therefore it seems as if the utility companies have a rather pragmatic view on the issue of smart energy community design. There had not been any discussion amongst stakeholders on system boundaries for the energy integration into the SEC planning, yet the view of the utility companies seems to be that SECs are a sort of ‘off-grid systems’, which aims at self-sufficiency. Utility companies regard this concept as impractical.

> ‘*On the thermal side, you can attach district heating to the smart energy community. But you can also scale down district heating so that you have a low-temperature grid inside the community, and that you build it for energy… future energy efficient buildings. So we can see that you can be attached to the larger system, but you can also design the community so that it initially looks like an island… However… we are influenced by our work and… I do not believe in 100% off-grid solutions’*
>
> Representative of Utility company
> (translated from Norwegian by authors)

The interviewed participants from utility companies emphasized this view further when we asked them to define the concepts SEC and ZEN. They regard SECs as ‘islands’ in terms of energy use and that they should be calculated as such. When asked how they define ZEN, they see it as broader than SECs.

> *‘Zero emission neighbourhoods should include everything, down to what people are having for breakfast’*
>
> Representative of Utility company
> (translated from Norwegian by authors)

When discussing these topics further, it became clear that the utility companies approached the two concepts SEC and ZEN as two competing ideals during the planning. SECs, on one hand, being ‘utopia’ in the sense that the utility companies do not commit to the idea that any Norwegian community should be ‘off-grid’ or planned independently; and ZEN, which they also perceive as impractical because it attempts to be too all-encompassing. The utility companies pragmatically seek something in between, and they exemplify this by calling for the cost/benefit view to be better included in institutional and governmental integration scenarios. They hence take an advisory role and see themselves as translators between the ideal and the feasible. This advisory role includes meeting general ideas of what meaningful resource use means to city planners, with suggestions that match the objectives of the city planners. For example, within the Oslo case, the urban planners seem to have the common view that ‘it is good to use what you have’ and that energy production locally should be visible locally to citizens, and this view is met by utility companies’ suggestions to include electric buses and to include visualization strategies to show energy use publicly to citizens.

> *'I believe that it is a good thing, to use optimally the energy that we have available, and that the citizens of Furuset should have ownership of the energy produced in the area'*
>
> City planner (translated from Norwegian by authors)

The advisory role of utility companies increases once the project approaches implementation stage. City planners and interviewees in the climate sections explain that the increased advisory role of one utility company in the projects is a result of two main issues:

- *The complexity of breaking down emission goals to project level actions:* The municipality finds it difficult to break down emission goals to building project level actions. Instead, other priorities overrun the environmental goals. For example, the need for a higher number of dwellings in Furuset and the priorities of the National Road Administration are misaligned with the environmental goals of Furuset, while the in ZVB case, the localization of the project is misaligned with the densification policy of Bergen. Further, there are no legal requirements in which municipalities can enforce higher environmental standards for buildings or a community beyond the technical standards. As a result, they explain that they witness that the overall emission reduction objective loses priority along the project timeline. They explain that this tendency to lose track of the target during the process, combined with the lack of competency that they experience regarding energy within the municipality, results in a strong dependency on the utility companies, who are the traditionally main advisers to energy policy within the municipalities.
- *Fear of increased workload and added complexity:* The inability to include energy from the early planning stage due to lack of incentives for utility companies, 'tradition' and misaligned mandates are listed as reasons for not integrating energy earlier on. Utility companies do not see why they should be included in start-up meetings between private builders and municipality. They currently do not see which incentives they have for being there before the project has been approved. Moreover, participants in the climate sections within the municipalities explain that if they ask for utilities to be included in start-up meetings, climate section staff explain that city planners and private developers are reluctant to include utility companies because they think more stakeholders will believe that the two SEC planning processes already are lengthy. They would like to see measures that can speed it up rather than add extra work through an increased number of stakeholders. In addition, city planners perceive their mandate to be the creation of good socio-economic communities, and that energy is not their main concern. It becomes difficult to prioritize energy integration and to work on energy scenarios extensively when the municipalities already feel unable to achieve the communities that they want due to the difficulties of stakeholder agreement and misalignment of public and private interests in the spatial planning. Because of this complexity, they rely on the utility company to influence the final energy design instead of intentionally managing it.

3.2 How do utility companies see their future role in integrated urban energy planning?

The utility companies express that the idea of a self-sufficient community per se is a threat to the current conventional business model of the major utilities in Norway. At the same time, they see that a ZEN way of thinking, in the way that they define it themselves, is an opportunity. They include the end-user aspect and end-user behaviour as part of the ZEN image; they regard the ZEN concept as a smart technology related opportunity where they can involve the end user more into energy choices. Several statements during the interviews indicate that they regard ‘smartness’ in terms of technology to be a way for them to keep the citizens connected to the national grid and to bridge the gap between an increasingly independence-seeking energy customer and a main electric grid dependent electricity provider. One of the interviewees illustrates their view on the future end-user scenario in the following quote:

> *‘In the future, Mrs. Hansen can sit in her apartment and tell her TV that she needs to go to the doctor. Then the TV will make sure she has an electric car charged from the carpool waiting for her. And she will have a smart meter in her living room telling her when the electricity prices are low so that she can wash her clothes.’*
>
> Representative of utility company
> (Translated from Norwegian by authors)

A participant from the utility company in the ZVB case explains that they are currently questioning whether they as an energy provider should play the role in designing the interfaces between the different solutions; mobility, energy use and user behaviour in general. In other words, if they should be involved in the integration of smart technology into buildings, apartments and transport. In the Furuset case, the utility company appears to be more interested in strengthening the role of their district heating system, and wish to influence the legal framework which allows them to require that buildings, old and new, are attached to their energy infrastructure. In the Furuset case, the utility company’s strong emphasis on district heating is met through suggestions by city planners to visualize the energy use locally. This is because extensive participatory processes at the beginning of the planning of Furuset raised the need for making the Furuset area more attractive to investors, and to increase local ownership. Further, the goal retrieved from the participatory processes, of reducing traffic through the center of Furuset, has led to the utility company making an agreement with an electric bus company, where the utility company will deliver energy to the local buses. The emphasis on socioeconomic values of district heating is also found in the argumentation of the utility company at Furuset:

> *‘the model that guides the energy label organization today focuses on delivered energy, and it disfavors both electricity and also district heating, because it is delivered, while internally produced energy is favored. …. In our view, it is easy to think that either [SEC] is a stand-alone island or it is not. We of course want to use district heat to as large as an extent as possible, from our system, and we think that it is socioeconomically great. We have a large surplus from waste combustion, which we want to use, and of course this influences what type of energy carrier is valued in a community system…let me take an Oslo-example. It is so that in district heating, 60% is based on surplus energy, energy that wouldn’t be used if it wasn’t attached to the waste combustion in Oslo. And then we have 10% of the energy structure attached to sewage pumps in Oslo, which if we had cut that, it would also not have been used. So…we apply services and exploit resources that if not would have been wasted. So, we regard these, as examples of* CO_2 *neutral energy carriers, energy sources[…] We see neighbourhoods as Oslo, we do not see neigbourhood as simply a cluster of dwellings. So if zero emission buildings are stand-alone buildings, neigbourhoods will also include our delivered [grid] thermal energy’.*
>
> Representative of utility company
> (Translated from Norwegian by authors)

The municipality city planners on their hand view their main mandate to ensure a 'good city' in terms of good living environments for their citizens. Of energy-related issues, they focus on localization of buildings and placement and are interested in finding ways to increase the use of bikes and walking. They want to see buildings that invite end-users to live sustainably and want to see buildings and communities that inspire people to not use private vehicles. They miss better inclusion of citizens' needs into the SEC plans and in this way support the utility companies' question about increased use of alternative scenarios for SEC planning.

3.3 Which measures may be taken within municipal planning of SECs to help manage the identified challenges and opportunities?

In Bergen, city planners, and climate section staff would like to see utility companies play a more central role in providing innovative solutions for reducing emissions, yet they are finding difficulties in negotiating with utility companies on SEC planning strategies:

> '*we for example propose that we would like some alternative suggestions on what kind of streetlights we want here… but then the utility company which provides for this [other] area say that they will not do this…*[other thing that the new alternatives depend on]'
>
> Representative of climate section
> (Translated from Norwegian by authors)

The municipalities believe that they can have a clearer influence on energy issues and the overarching emission reduction goals through:

- Increased legal agreements to demand the inclusion of energy issues and utility companies' involvement earlier.
- Tools to help them achieve the right sequence of implementation steps in a community, to ensure that the needs of citizens' well-being and private interests are met. Their main concern is localization that reduces private car traffic and that services such as schools and public meeting places are central also in SEC planning.
- improved in-house competency on energy and clear responsibility on who within the municipality has the mandate to integrate energy planning into work to lower emissions.

Utility companies, however, explain that they think they play a useful role as advisors to the politicians on how the future communities of Bergen and Oslo should be designed in relation to energy use, yet they perceive that the municipalities lack clear visions. This discourse is in line with the negotiation difficulties described in research on the results of liberalization of the utilities in Europe [14, 16, 20].

Moreover, the lack of socio-economic cost-benefit analyses in the current planning tools for SECs makes it difficult for the municipalities to manage the utility companies' influence on the final design. The utility companies agree with the private developers on the fact that it is cost and supply security that drives the decisions of private developers instead of what they refer to as a 'green profile'. Yet, they see the need for the municipalities to present a clearer view of what they want. Finally, utility companies would like to see increased incentives from the side of the municipality to ensure energy renovation of existing buildings. This energy renovation must be viewed in relation to the district heating regulation in

Norway where municipalities may impose on buildings an obligation to connect to a district heating system within a defined concession area. This obligation has impacted the growth in district heating. Utility companies see that it is relatively easy to regulate newer buildings in this regard, while lowering emissions in the Furuset case optimally will require energy renovation and obligation to connect to the district heating system also for the existing buildings. ZVB is different, as it is planned to be built on an undeveloped area where building renovation isn't an issue. Bergen city planners and climate section would like to see more SEC projects within the densification zone of the city in the future, hence the participants in both municipalities call for tools and incentives that can help them plan and to transform existing buildings, communities and neighbourhoods.

4 DISCUSSION

Utility companies in Furuset and ZVB were involved late in the planning process of the two smart energy communities. This shows that the two cases have followed a traditional urban planning process in which planning considers mostly the spatial characteristics of a certain area, which is carried out through zoning plans. Energy planning is then carried out only after these spatial plans are made, and the energy planning is often left to the utility companies (Kuronen *et. al.*, 2010). This is consistent with what is expressed by interviewees involved in the planning of the two case studies; energy planning seems to be a completely separate process taking place only after land-use planning is completed. Previous research has shown that this is how the planning process in Oslo normally is practiced (Resch & Andresen, 2017). Still, utility companies' influence on priorities in the final SEC design seems to be strong due to their resources competency, and historical connection to the municipality, as well as the lack of business models for renewable energy that suits the Norwegian monopolistic energy market. According to the climate section staff in Bergen and Oslo, earlier inclusion of utility companies in the planning process could result in a better interplay between the main utility providers and renewable energy services within the SEC, as well as more focus on innovative approaches to lower emissions. They perceive that innovative results depend on a better interplay between the traditional utility providers and new ideas for local energy generation and business models.

4.1 Utility companies' role in definitions and strategies

In line with sustainable cities research 'Competing conceptions of sustainable cities lead to the development of a range of initiatives, strategies and plans, and the emergence of alternative logics of environmental innovation' [21]. Regarding the view on the meaning of SEC, the utility companies operate with two narratives for urban energy futures:

a. The 'island' of 'Smart Energy Community'. The isolated calculation of a clearly defined area of buildings and infrastructure producing its own energy and seeking independence. This narrative is regarded as a threat to the current conventional grid business model of the major utilities in Norway.
b. The 'all-encompassing' Zero Emission Neighbourhood where participants believe everything 'down to what is eaten for breakfast' is included.

The utility companies relate to these narratives in a pragmatic way, but different in the two cases. Both of the above-mentioned views are presented by the utility companies as research ideas that do not take into account costs and benefits, which they in turn can provide. This means that the utility companies fill an important practical function that is invaluable for the municipalities who do not have strong energy competencies in-house. In the Bergen case, which is regarded as belonging to the 'island' thinking, the utility company answers to the foreseen 'threat' of energy independence-seeking customers by proposing that the utility company could offer services within homes which make peoples' energy reality simpler and more convenient.

In the case of Oslo, the utility companies become influencers and argue for the benefit of using the district heating grid, and wishes to expand this infrastructure. In both cases, we see that utility companies move from the outside of the planning process into a role where they seek to keep their market share.

General ideas of what meaningful resource use means to city planners are met by suggestions by utility companies. For example, within the Oslo case, the urban planners seem to have the common view that 'it is good to use what you have'. This narrative is found in how they value the Furuset area and its existing value historically and socially, and their wish to keep this value through an inclusive planning processes. The narrative is then recovered in the ideas by city planners that the ownership feeling of citizens of Furuset will be increased if they can see 'what they have' and visualize energy use and production. The idea that local energy production should be used locally to create ownership matches with the first narrative of 'island' thinking of SECs. This narrative and the view of the citizens of Furuset, as a collective, seem to affect the definitions of 'green' energy.

4.3 The envisioned future role of utility companies

Participants contributions indicating that utility companies see the self-sufficient SEC idea as a possible threat to their current business model, and their interest in discussing new ways to make ZEN and SEC thinking feasible by matching their definitions and strategies with their own services. From this, it becomes evident that utility companies are aware of their need to rethink their strategies in relation to urban planning. At the same time, the different narratives in the two cases also show that the utility companies do not have a set definition space to decide what a Smart Energy Community should achieve and to discuss alternative options regarding energy provision. Instead, they show that their experience strengthen their already prominent advisory role to make the energy infrastructure feasible and cost effective, and that will make sure they keep their role in the energy planning in the future. They also see the current trend of customer energy independency as a threat and that the involvement with municipal planning can be a way for them to manage this threat. The lack of discussion on whether the grid electricity and municipal waste heat are emission-free, together with the lack of discussion on how to *reduce* energy through SEC design, is symptomatic. This exemplifies how utility companies are involved in SEC planning, yet it also shows the need for competency within the municipalities on integrated energy planning and its link to emission reduction. Regarding the future role of utility companies in Norwegian municipalities, with new energy technologies on the rise, the utility companies who are providing centralized energy solutions may feel the pressure from start-ups as well as from individual consumers deploying decentralized energy solutions such as solar systems and heat pumps. This is seen as a clear threat to their business model, and the utility companies have already initiated plans to take an edge in this arising decentralized energy market according to utility participants.

4.4 Improving municipalities' ability to manage the development of SECs

There is no clear and common definition of what zero emission means on a community scale. Instead, the stakeholders compose their own understanding as the project progresses, and adjust strategic measures to what the current legal framework allows. City planners lament that this legal framework currently is limited to the design of individual buildings, and they wish for legal frameworks that can assist them in demanding energy related issues to be included earlier.

5 CONCLUSIONS AND FURTHER WORK

Based on the two cases we see that a lack of agreement on what a SEC design should include and how it should be planned leads to the involved stakeholders making decisions along the way based on logics constructed by a composition of their individual ideals. City planners focus on fulfilling what they perceive as the citizens' needs, while the utility company focuses on their future business model opportunities and how to apply their experience in a beneficial way. The data analysis further showed an overall image where the utility companies' perspectives on future roles and the perceived threat of local energy production had hued their input to the definition and strategies within the SEC planning. It further shows that in lack of clear definitions, different forms of collaboration between municipality planners and the utility companies had shaped somewhat different strategies for the two projects.

We see that in the current planning of the two smart energy communities, utility companies become involved late in the planning process. Despite their late arrival to the process, utility companies quickly take a leading role in deciding the definition space of what a smart energy community is within that project, and in the municipality planning practice in general. Once the utility companies are on board, the view of what the SEC should or could look like is adjusted, for example from the vision of 'zero emission resources' towards the vision of 'exploiting locally available resources' and optimal use of the utility companies' services.

In our two studied cases of SEC planning processes, it is interesting to see to which extent municipalities look to the major utility companies to understand how to realize the final SEC plans. We see that the utility companies add the feasibility aspects and their prioritized agendas of cost/benefit and energy supply security to the discussion. They further contribute to strategic thinking based on their envisioned future role. Taking this lead role is not due to malintention from the side of the utility companies, but rather it may be a result of the historically monopolized Norwegian energy market. Still, it is an argument for finding SEC planning approaches that manage to broaden the scope to include more innovative and alternative energy scenarios. Parts of the reason that utility companies influence the definitions is also that stakeholders perceive that ZEN and SEC thinking is 'island' thinking and that this view is impractical in the Norwegian context where connection to the grid is an ideal and the idea of 'supply security' is strong. This shows the need for research that exemplifies integrated design, which also works aligned with cost/benefit frameworks and that can also work in areas which combine existing and new buildings and infrastructure. The findings illustrate a clear need for definitions and strategies that can strengthen the role that municipalities must take to manage building, community, and neighbourhood planning towards a zero-emission vision.

Both Oslo and Bergen have ambitious goals for reduction of greenhouse gas emissions in the years to come. Emission accounting is, however, not straightforward. In the same way that the definitions of SEC and ZEN are unclear, so are the definitions of the municipalities' emission targets. The energy use in urban areas consists of the direct consumption of energy for the operation of industries, infrastructure, buildings, and transportation of people and goods, as well as the indirect (embodied) energy in materials of the built environment and the consumed goods. It is not clear which emissions should, and should not, be attributed to the municipality. There is a need for further work on developing calculation methods and tools for effective accounting of these issues in the planning of SEC.

In sum, our findings support the need for academia to play a guiding role in the municipalities work to plan smart energy communities and zero emission neighbourhoods. Further work in the PI-SEC project therefore include developing tools and strategies for integrating energy planning based on the two cases; and to test them in the planning of Smart Energy Communities in Norway.

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Paper S.III

Visualisation of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality

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The paper's context in the thesis:
The database is applied for visualization in Virtual Reality of the embodied emissions in a neighborhood setting.

Visualisation of KPIs in zero emission neighbourhoods for improved stakeholder participation using Virtual Reality

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Abstract. This paper addresses the role of virtual reality in addressing the specific challenge of the increasing complexity and decreasing usability when dealing with the level of detail required to model a zero emission neighbourhood (ZEN).[1] In such neighbourhoods, there is a need to handle both 'top down' neighbourhood level data with 'bottom up' building and material level data. This can quickly become overwhelming particularly when dealing with non expert users such as planners, architects, researchers and citizens who play a key part in the design process of future ZENs. Visualisation is an invaluable means to communicate complex data in an interactive way that makes it easier for diverse stakeholders to engage in decision making early and throughout the design process. The main purpose of this work has been to make ZEN key performance indicators (KPIs) more easily comprehensible to a diverse set of stakeholders who need to be involved in the early design phase. The paper investigates how existing extended reality (XR) technologies, such as virtual reality, can be integrated with an existing dynamic LCA method in order to provide visualise feedback on KPIs in early phase design of sustainable neighbourhoods. This existing method provides a dynamic link between the REVIT Bim and the ZEB Tool using a Dynamo plugin.[2] The results presented in this paper demonstrate how virtual reality can help to improve stakeholder participation in the early design phase and more easily integrate science-based knowledge on GHG emissions and other KPIs into the further development of the user-centered architectural and urban ZEN toolbox for the design and planning, operation and monitoring of ZENs. [3]

1. Introduction

In the future, municipalities must handle a completely different level of complexity in society. In order to have well-functioning cities, cities must improve how they utilise their resources and how they engage with technologies in different ways. A smart city will use digital technologies to enhance performance and wellbeing, to reduce costs and resource consumption and to engage more effectively and actively with its citizens. In this context, the objective of this work is to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) and zero emission building (ZEB) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts. [4, 5] The aim is to evaluate how virtual reality can help communicate, involve and improve participation from diverse stakeholders involved in the ZEN design process including politicians, municipality planners, design/planning practitioners, and citizens.

Current methods for visualizing semantic information are mostly limited to coloured map overlays, 2d and 3d-graphs or values spread across maps. The potential of using Immersive technologies, such as VR to enable users to explore and interact with real design projects is investigated in this paper, as well as, the extent to which it can be used for the planning of complex infrastructures and the visualisation of multiple key performance indicators (ZEN KPIs). This VR approach is particularly of interest to diverse experts and decision-makers in order to provides them with the means to explore results early in the design phase and on-site. Full details related to the research presented in this paper can be found in Løvhaug and Mathiesen. [6]

1.1. ZEN Definition, KPIs and pilot project

1.1.1. ZEN Definition and ZEN KPIs

The vision of the ZEN Research Centre, together with its industrial partners, is to create zero emission neighbourhood in smart cities (ZEN). [1] In the ZEN Research Centre, a neighbourhood is defined as a group of interconnected buildings with associated infrastructure, located within a confined geographical area. A ZEN aims to reduce its direct and indirect greenhouse gas (GHG) emissions towards zero over an analysis period typically of 60 years, in line with a chosen ZEN ambition level with respect to which life cycle modules, buildings, and infrastructure elements to include. The ZEN assessment criteria and key performance indicators are divided into seven categories (GHG emissions, energy, power/load, mobility, economy, and spatial qualities), and each of these categories is divided into several assessment criteria. [4] The assessment criteria are then divided into several key performance indicators (KPIs) which are listed in Appendix A.

1.1.2. ZEN Pilot projects

In the context of the ZEN Research Centre, pilot projects are geographically limited (primarily urban) areas in Norway and serve as innovation hubs where researchers, building professionals, property developers, municipalities, energy companies, building owners and users, test new solutions for the construction, operation, and use of neighbourhoods in order to reduce the greenhouse gas emissions to zero on a neighbourhood scale [4]. Various stakeholders will have different influences on a ZEN pilot area at different times during the development of the area. In this case, key stakeholders include Trondheim municipality and the project owner NTNU, as well as, other stakeholders. The pilot site at Nidavoll Skole [7] in Sluppen is located in the larger ZEN pilot project called The Knowledge Axis [8] and culminates in Sluppen, a mainly commercial area that is planned to be developed into a multi-functional neighbourhood.[9]

1.2. Virtual Reality

There exists a variety of techniques, tools and technologies for displaying data using diverse media. Examples includes 2D-based screens like traditional desktop applications, tablets or interactive multitouch solutions. On the other hand, there are more immersive tools which are covered by the term Extended Reality (XR), which is an umbrella term to refer to all real-to-virtual combined environments such as Augmented Reality (AR) and Virtual Reality (VR). While more traditional user interfaces like desktop applications which are more advantageous when displaying and navigating through large quantities of text-based data, whereas XR is more suited to creating an experience for the user. Solutions span from showing information on a tablet, to strapping the user into a haptic suit with a head mounted display. Due to the immersive effect of head-mounted displays, the user can interact with the data in a way that is limited in desktop-applications. For this project, it was decided to further explore the possibilities of visualizing data using VR. In recent years, the main focus for VR has been centred around the entertainment industry. This focus has driven the innovation in the field where different manufacturers are promising better and cheaper solutions, and has also made the technology available for consumers. There has been a large increase in technologies allowing for users to interact and alter a virtual environment, and technologies suited for immersive experiences.

Virtual Reality is a computer-generated experience which takes place in an virtual environment. Normally the user wears a head mounted display (HDM) with two individual images for both eyes, creating a depth perception. The HMD is tracked by either itself (inside-out) or sensors in the room (outside-in). This allows the application to mirror the position of the user in the real world, in the virtual world. The user can interact with the environment by using speech, hand-tracking, eye-tracking or input devices, where the most common is a form of controller which is tracked in all directions, mimicking the user's movements. VR technologies are potentially groundbreaking for visualising data and creating an experience for the user. It is now possible to not only showcase the data and environment on a 2D screen, but also put the user in the actual environment itself. Combined with different techniques of data visualisation, the overall aim is to leave an impression on the user, as found in a study from University of Maryland where their results showed that participants remembered on average 8.8% more of information presented in VR.[10] By using existing floor plans one has the ability to create a digital twin of the buildings. With this 3D-model one have the ability to re-create a realistic replication of the environment with connected information displayed on and around the 3D-model. In addition to the data visualisation, it is also possible to display the building in a realistic way before the building is even constructed. This use case can make it easier to communicate data and engage diverse stakeholders early in the design process. There are several VR products available, all in different price-ranges which can be defined in two sub-categories; low- and high-end.

The focus of this paper is on the results using high-end VR involving the development of the HTC Vive [11] for use in our application using the Unity 3D software[12] which works well with all known VR headsets and controllers supporting OpenVR. The reason for choosing the HTC Vive was also because of its availability and ease of use. As opposed to the low-end sub category, this kind of equipment is in general more expensive. While the application relying on the low-end equipment can be tried at home, the high-end solutions often needs to be made available for user at for example stands or promotional events. The technology needed to fulfill the requirements in the high-end sub category varies depending on the application. For less intensive tasks, it can suffice to use with a mid-range desktop computer, but for applications which demand more processing power, it is recommended to use a top of the line GPUs. VR head mounted devices (HMDs) have seen rapid development, which initially was mostly driven by the fast hardware iterations of the smartphone industry. The current wave of VR devices began with the Oculus Rift Kickstarter campaign in 2013 accumulating close to 2.5 US dollars in pledges.

Table 1 Development of of VR devices based on popular HMDs

Date	Description	Resolution per Eye	Horizontal View	Features
3.2013	Oculus Rift DK1	640x800	90	only 3 DoF tracking
7.2014	Oculus Rift DK2	960x1080	90	
4.2016	Oculus Rift CV1, HTC Vive	1080x1200	90	
10.2017	WMR Lineup	1440x1440	90	inside-out tracking
4.2018	HTC Vive Pro	1440x1600	90	
2.2019	Pimax 8k	3840x2160	170	

2. Method

2.1. *Research Method*

The Design Science Research [13] has been used in this research and focuses on three different cycles, as explained by Hevner [14]. This includes the *relevance* cycle, *rigor* cycle and *design* cycle. In short, the *relevance* cycle ensures that the result of the research fits into the intended usage area. The *rigor* cycle aims to ensure that the research is representative of the 'state-of-the-art' in the application domain. Finally, the *design* cycle facilitates a development process which consists of several iterations with rapid evaluation.

The prototype used in this research is the ZEN pilot project at Nidarvoll Skole [7] as the main design project, and gives the user the ability to view the pilot project from both a building- and neighbourhood perspective. The embodied carbon data is gathered from an Excel based tool called The ZEB Tool [15]. The pilot project is in a very early stage of design and since there is limited available data, the data used in the prototype is based on another school named Østensjø School in Oslo. There are also limitations regarding to the availability of a 3D model, however, by using existing building plans, an initial Revit model of the main building has been created. New models will be added to the system in the coming months. By using this project for the ZEN VR application, the results from retrofitting and new buildings with data from early phase design can be compared to data from different stages of design to visualise how different design or materials changes impacts the different KPIs in a design project.

2.2. Data Source and LCA Method

This works builds upon the work already developed by Houlihan Wiberg together with students to develop a visual LCA method, using a user interface in the form of a dashboard, connected to an integrated dynamic Revit 3D and the ZEB Tool [16, 17]. In this initial version of the developed VR software, the focus is on visualizing the KPIs related to carbon embodied in the production, transport, and replacements of building materials. The embodied carbon data from the ZEBTool [15] is stored together with data from other sources in a MySQL database which is specifically developed for the purpose of structuring and storing building LCA studies in a comparable and accessible format [18], so that the data can be used in applications such as the one presented in this paper. This solution allows easy online access and ensures that the user is always presented the most up to date information and that it is easy to add new information relevant for the application. Furthermore, the database has a set of additional building LCAs which are used to set reference values when benchmarking the results of the case study. In order to be able to run the application offline, the application has a local copy of the database which it used when there is no database connection.

2.3. User study and questionnaire

The VR application and its potential was evaluated through the use of semi-structured expert interviews and its usability, through a questionnaire. The participants of these two methods of data collection tes the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the research questions. The strategy for obtaining informants used was primarily the snowball technique. To evaluate the user interface and ascertain the degree of usability when using the system, a questionnaire was designed. The questionnaire was designed after the principles of a Likert scale. The general methodology used when conducting the user study has been semi-structured expert interviews which allows one to get the chance to ask the informant specific questions, but it also allows for unexpected turns. There were three participants in each of the interviews including the informant and two of the authors of this paper which allowed for one to lead the interview and the other to take notes on essential parts of the interview. However, the main collection of data were audio recordings that were later were transcribed. A detailed description of the user study and questionnaire methodology may be found in Løvhaug and Mathiesen [6].

2.4. 3D Model – Unity Software - VR

For the visualisations to be as realistic as possible, the buildings are exported from the BIM software Revit [19]. The models are then converted Autodesk Maya [20] before importing them into the Unity 3D, because when Revit exports 3D modes, it does not use a naming convention resulting in some building elements end up being unnecessarily detailed, making the app run slow. The choice of using BIM models in the application ensures that the building models are directly linked to the work of the architects, and visualisations can therefore be part of an iterative design process.

3. **Results**

The preliminary results in this paper describe the application prototype, and the informal and rapid feedback from user testing in order to visualise ZEN KPIs and improve stakeholder participation early and throughout the design process. The results provide a way to visualise a selection of KPIs from the an actual ZEN pilot projects at different levels of detail. Non-expert users of the application can see how this neighbourhood is performing compared to other projects in the vicinity. It is also possible to walk around the neighbourhood, inspect individual buildings and identify which building components and materials are the highest driver of emissions. The application also has the flexibility to add new KPIs when more data becomes available for each pilot.

3.1. VR Application Overview

The Research Centre on Zero Emission Neighbourhoods in Smart Cities have defined a set of assessment criterias and key performance indicators which are used to track, evaluate and validate the progress of ZEN pilot areas. The developed prototype builds upon existing work conducted at the Fraunhofer Research Centre in Singapore, where several different VR and AR-applications have been developed, one of which is used to assist the Housing and Development Board in Singapore. [21] This application utilizes VR in a way that correlates with the vision of the end product of our research. The application aims to visualize data for the Nidarvoll site in light of a selection of these predefined criterias. In order to achieve different levels of detail, a three layered model with the following views which were developed in the VR application as shown in table below:

1. *Full view*
   This view displays all available projects in the Sluppen area. The map of the neighbourhood and surrounding area are are put on a table-surface and the user have the ability to get an overview of the whole area. Relevant KPIs for this view would be aggregated values from all buildings and other high level high level KPIs such as mobility, economy and energy efficiency.

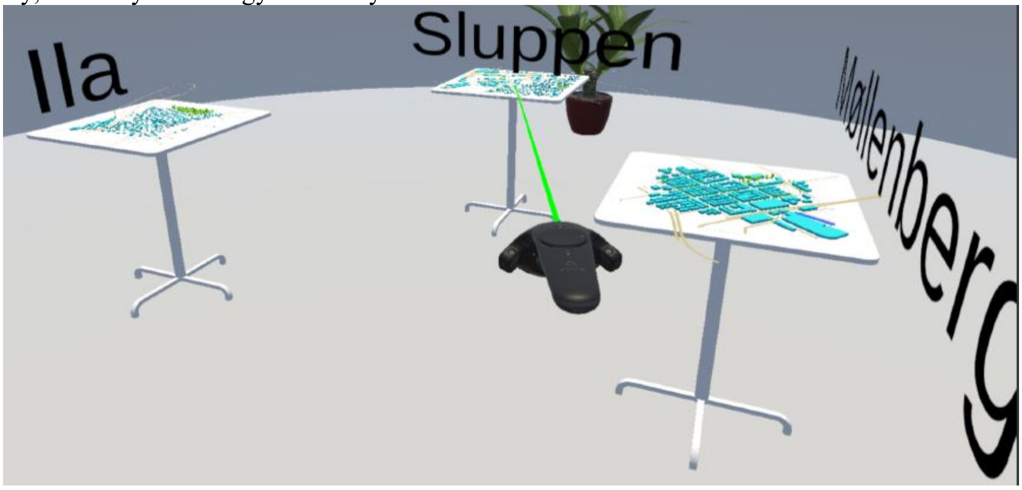

Figure 1. Full View of the Sluppen area Using VR

2. *ZEN-view*
   When selecting a specific pilot project in the full view the user gets transported down one layer, and is presented with the ZEN view. In this view the user stands in a small scale model of the environment and have a ability to teleport around and inspect each part of the neighbourhood. The user can, to begin with toggling between two different KPIs i.e. GHG emissions and energy consumption/generation. Emission values are presented as either a colorisation of the buildings or a column visualisation, both of which have a possibility to be further developed in the future. For comparing the score of the buildings in the neighbourhood, the user has two options: 1) evaluate the buildings totalCO_2eq/m^2compared to the total $CO_2eq/m^2$for all buildings present in the pilot area. 2) Evaluate the buildings totalCO_2eq/m^2compared to the total $CO_2eq/m^2$for all buildings that are present in the database. To put these numbers into context and to engage the user, it is possible to visualise the weight of the CO_2eq emissions in terms of vehicles most users are familiar with using images of airplanes and cars. In addition, it is possible to get an explanation as to what the emission equals in kilometers driven in cars and round world trips in airplanes. This is shown on the left in Figure 2. Energy is visualized as a bar which displays energy consumption versus energy production for each building. The user will also be able to see the sum of consumption and generation. In the next stage of development, when the energy KPI has actual data, the user would be able to get examples of feedback for energy usage.

Explanation
The total emission of Oestensjoe skole is 815.06 tonnes of CO2e. This is equal to the weight of 5 Boieng-787 and 63 average cars.
With this amount of CO2 you could drive 6269709.5 km, or fly 156.45 times around the earth.

Oestensjoe skole
Floor area: 3629 m2
Total emission: 815.06 t CO2e
Emission pr m2: 0.22 t CO2e/m2
Electricity usage: -0.1 KW/h

Explanation
Visualizing tonnes CO2 per square meter of buildings in neighbourhood relative to the average emission of the neighbourhood. Green is below the average, red is over. Average is: 0.3 tCO2 / m2

Figure 2. Snapshot in ZEN View of the Sluppen area using VR to visualise emissions of buildings

3. *ZEB-view*

If the user selects one specific building in the ZEN view, they teleport down to the ZEB-level (Building level). This view focuses on one particular building, and serves the purpose of communicating the KPI GHG-emissions for both each building part and every material in said building part. This view has two models; one 1:1 model where the user can teleport inside and experience/inspect the building. The other is a "dollhouse"-model where the user can inspect and interact with the building by clicking on building parts. The user is also presented with a menu for toggling between different building parts. The KPI score is visualised using colorisation similar to the ZEN-view. The user can choose two different approaches; the first compares the performance of each building part to the total emission of the building. The second approach weights the building mass as part of the equation and returns a score based on both the emission and building part mass compared to total building mass. If the user selects one specific part, they get presented with material information in tabular form for the selected element. In addition to the tabular form, the materials used will be visualised in actual size and weight so the user can put the quantity of materials into context. The intensity of the emission is visualized by using the same columns from ZEN-View. The purpose again is to give the user a more immersive experience and to put the numbers into context.

Inner walls
Total Quantity 478.355 t
Total Emissions 114.3376 t CO2e

INNERWALLSFLOOR3
Weight 478.355t
Emission 114.338 ton CO2e
Kg C02 pr Kg Material 59.794 CO2e / mass

Figure 3. ZEB View of a building using VR to visualise emissions and by listing materials in tabular form

3.2. *Results of user tests and questionnaires*

After conducting some informal user-tests on subjects without prior knowledge regarding sustainable neighbourhood design, the results show that average citizens and other stakeholders do not find it easy to understand what the emission data means in relation to the neighbourhood context, and designers find it difficult to understand how to integrate this data into the design process. As a result, a design has been developed which focuses more on the immersive experience and visual display of data as a means to communicate complex KPI data. An example of this, is the visualisation of the amount of timber used in construction not only as a number, but also as as number of virtual logs stacked. Another example is, that the contribution of transport related emissions is indicated as a number of different vehicles and GHG emissions for travel distance and intensity of pollution is indicated in size and colour.

It was found that when working on the application, that by using high-end VR equipment, a more immersive experience is achieved which results in more engagement from the user and facilitates easier interaction and feedback with the ZEN KPIs. The results also show that users enjoy exploring the novelty of a virtual environment and because of this, it was decided to only implement a small portion of the pilot area, so the user would not get lost in the experience, but rather focus on interacting with the relevant information and specific KPIs for the area. It was also found that the *Unity 3D* software allows for quick prototyping and development for multiple platforms at once in addition to making a high quality result.

Another finding was that size matters. Some of the visualisation methods, first deemed unnecessary, ended up being the most important in making an impression on the user. By using only colour visualisation of the emission data, the user does not fully understand the significance of the emission results. However, it was found if different sizes of columns are used instead to communicate the significance of the level of resulting emissions from the building, it was found that the users more easily understood this data in this more visual context. One of the test-subjects stated when looking at a large, red column that she *"I would not like to live in that house"* due to the associated high emissions.

4. **Conclusion and Discussion**

The results of this paper show that this ZEN VR approach provides for a new and intuitive way of interacting with and viewing multiple KPIs simultaneously. This approach presents a new way of combining KPI data with BIM models early in the design process. By utilising visualisation methods which inspire and engage diverse stakeholders to explore the environment and learning by putting numbers into context, the ZEN vision of a sustainable neighbourhoods can more easily be communicated by diverse stakeholders. VR is a valuable tool to engage users with no prior knowledge of ZEN or KPIs, to put data into context and to more easily understand the meaning and size of the numbers presented. This VR approach improves communication with and between stakeholders and provides a means to overcome traditional interdisciplinary barriers. It was also found that high end equipment offers a better immersive experience by having better image quality, performance and input possibilities. This makes it easier to engage the user and keep their attention in the application while learning useful information, but with an increased cost and more cumbersome setup.

The research explored the utilization of virtual reality as a tool for engaging and interacting with emission data in new and immersive ways. A VR application, called ZENVR, was developed through several iterations by connecting an existing MYSQL database, containing life cycle assessments of 11 projects in Unity 3D. Furthermore, the application and its potential was evaluated through the use of semi-structured expert interviews and its usability through a survey. The participants of these two methods of data collection all tested the application on the same terms, with a set of predefined tasks. These were conducted in order to answer the objectives of this work which was to investigate how visualisation methods, such as, Virtual reality (VR), can support the evaluation of zero emission neighborhood (ZEN) design concepts with respect to key performance indicators, such as, greenhouse gas emissions and other potential environmental impacts.

The results of this study found that virtual reality is a good platform for communicating and visualising complex data including the KPIs in sustainable neighbourhoods, for not only researchers but also for the general public. ZENVR can be used as a data visualisation tool for presenting data in a understandable format by creating a presence inducing environment which subsequently may result in an emotional experience when interacting with the application. In ZENVR we have shown that these principles can be used to visualize the KPIs from ZEN. These visualisation methods are exemplified through greenhouse gas emissions related to the transport and use of materials, but the principles are transferable to numerical data in general.

In terms of which form of data visualisation are most beneficial for comprehending the KPIs for different user group, it was found that ZENVR allows for selecting between several forms of data visualisations. Expert interviews revealed that professionals preferred traditional visualisation approach i.e. columns, colors and numbers when looking at KPIs. It was further discovered that in order to make a lasting impression, which ultimately is the goal of ZENVR, one have to use visualisation methods which appeal to the human emotions. This can be achieved by anchoring the visualisations to human factors by using the principles mentioned earlier, for instance using sizes to make the user feel small or movement of objects for dramatic effects. The visualisation type which made the biggest impact on all users was when numbers were put into context by using relatable objects from everyday life.

In relation to how can VR be used to improve stakeholder participation in sustainable neighbourhood projects, the results show potential areas where ZENVR can be used to improve stakeholder participation include citizen engagement, promotion and the advertisement of ZENs, tool for interdisciplinary communication and collaboration between professionals. With its natural immersive properties, VR has proven to be a suitable platform to spark engagement among its users. Through a well designed VR environment, highlighting the beneficial parts of an environmental friendly neighbourhood, all subjects agreed that this has a huge potential to promote sustainable neighbourhoods. In addition, VR allows for displaying data in new perspectives making it understandable for different stakeholders, reducing the barriers of interdisciplinary communication and collaboration.

5. **Further work**

The application in its current state is experimental and should be viewed more as providing a foundation for further development. Further work should investigate how more KPIs can be included in the application and the associated effect on stakeholders. In addition, when the application is more complete and thorough, user-testing might reveal if the usability improvement suggestions from the latest iteration are indeed useful. From a technical point of view, some alterations and features which might benefit the application arose from conducting user tests and interviews. These mostly centred around the user interface and how it might be changed to better suit the user's needs and understanding. It would be advantageous to test the application with other virtual reality systems to test its compatibility and possible adaptations that may be necessary.

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Appendix A

Paper S.IV

GHG emission requirements and benchmark values for Norwegian buildings

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Statistical benchmark results from a collection of case-buildings.

GHG emission requirements and benchmark values for Norwegian buildings

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Abstract. As a response to the Paris agreement, Norway is committed to reducing greenhouse gas (GHG) emissions by 50 percent by 2030. Highly energy-efficient buildings have a greater proportion of embodied GHG emissions from material use (55-87%) compared to operational emissions. A new national standard, NS3720:2018 a methodology for greenhouse gas emission calculations for buildings, has harmonised the life cycle assessment (LCA) calculation of environmental impacts arising from Norwegian buildings and has led to an increase in LCAs. This paper aims to collect life cycle GHG emission data on Norwegian building case studies to help form recommendations for national GHG emission requirements and benchmark values that can be used by the Research centre for zero emission neighbourhoods in smart cities (FME ZEN), Futurebuilt and in Norwegian building codes (TEK). To do this, a statistical analysis of a reference sample is carried out to provide bottom-up derived reference values. Empirical life cycle GHG emission data results are collected from Norwegian building case studies in the reference, design and as-built project phases, sampled from Norwegian programmes and research centres such as Futurebuilt, Framtidens Byer, ZEB and ZEN. Altogether 133 Norwegian building cases have been gathered from 2009-2020, covering 1,023,738m^2 of heated floor area for 49,360 building users. A functional unit of '1m^2 of heated floor area over a building lifetime of 60 years is used. The results show an interquartile range of 240-492 kgCO$_{2eq}$/m^2 or 4-8.2 kgCO$_{2eq}$/m^2/yr, a median of 396 kgCO$_{2eq}$/m^2 or 6.6 kgCO$_{2eq}$/m^2/yr and a mean of 324 kgCO$_{2eq}$/m^2 or 5,4 kgCO$_{2eq}$/m^2/yr for all building typologies in the as-built phase. These results can be used to form initial indications for GHG emission requirements and benchmark values in Norway.

1. Introduction

The United Nation's sustainable development goals (UN SDG) focus on a range of issues to be addressed by society [1]; including sustainable cities and communities (SDG 11), responsible consumption (SDG 12) and climate action (SDG 13), which are also some of the issues addressed in this paper. As a response to the Paris agreement in 2015 [2], Norway is committed to reduce greenhouse gas (GHG) emissions by 50 percent by 2030 compared to 1990 levels. At the European level, the revised directive on Energy Performance of Buildings (EPBD) requires that all new buildings should be nearly zero energy by 2020 [3, 4]. For most passive houses, GHG emissions from the production of building materials are equal to the emissions from operation throughout the building lifetime [5]. However, research shows that highly energy-efficient buildings have a greater proportion of embodied GHG emissions from material use (55-87% of embodied GHG emissions) where the building envelope makes up ca. 65%, and that construction phase emissions can equal operational energy use emissions [6-8]. NS3720:2018, a methodology for GHG emission calculations for buildings, has harmonised the life cycle assessment (LCA) calculation of environmental impacts arising from buildings in Norway [9], and has led to an increase in life cycle GHG emission assessments of Norwegian buildings. Creating national benchmarking and target values for buildings from this data will be a valuable resource for the decision-making process in improving the environmental performance of buildings [10].

The aim of this paper is to collect life cycle GHG emission data on Norwegian building case studies to help form recommendations for national GHG emission requirements and benchmark values for different Norwegian building typologies that can be used by the Research Centre on zero emission neighbourhoods in smart cities (ZEN Research Centre), Futurebuilt and in Norwegian building codes (TEK) [11, 12]. The paper starts by outlining the background and methodology for data collection and developing national greenhouse gas emission requirements and benchmark values, it then presents the results. A discussion on data collection and the development of GHG emission requirements and benchmark values takes place before concluding remarks are given.

2. Background

The world green building council (WGBC) urges governments to commit to occupying only certified net-zero carbon buildings before 2030 and encourages NGOs to develop certification programmes for net-zero carbon buildings as well as create roadmaps, incentives and tracking systems for the rapid development of net-zero carbon buildings [13]. They envision all new buildings, infrastructure and renovations to have 40% less embodied carbon and be zero operational carbon by 2030, and that all new buildings, infrastructure and renovations will have net-zero embodied and operational carbon by 2050 [14]. The WGBC define a net-zero embodied carbon building as highly resource-efficient with upfront carbon minimised to the greatest extent possible and all remaining embodied carbon reduced or, as a last resort, offset to achieve net-zero across the life cycle [14]. Building life cycle assessments (LCA) have commonly been used in building certification programmes such as LEED (US) [15], DGNB (Germany) [16], BREEAM (UK) [17] and Level(s) (EU) [18]. The International Energy Agency (IEA) Energy in Building and Communities (EBC) Annex 57 has analysed over 80 building case studies and found that the product stage (A1-A3) dominates total embodied emissions at 64%, followed by replacements (B4) at 22% and waste treatment and disposal (C3-C4) at 14% [19]. They also found that embodied GHG emissions for the product stage are around 2.1 $kgCO_{2eq}/m^2/yr$ for refurbished buildings (3.8 when including replacements), 3.5-6.6 $kgCO_{2eq}/m^2/yr$ for office buildings, 3-5.3 $kgCO_{2eq}/m^2/yr$ for residential buildings and 2.5-10 $kgCO_{2eq}/m^2/yr$ for school buildings [19]. To follow, IEA EBC Annex 72 will assess life cycle related environmental impacts caused by buildings from 2016 - 2021 [20, 21]. In addition, the forthcoming ISO 21678 offers a method for the development of benchmarks for sustainable buildings [22].

In 2013, the Netherlands became the first European country to introduce legislative requirements to report embodied material impacts from buildings [23]. Hollberg et al. discuss how environmental benchmarks can support the design process and present a method for combining a top-down and bottoms-up approach to encourage design guidance at the material or element level [24]. In Switzerland, the Swiss energy efficiency path provides target values for operational, mobility and embodied impacts based on a top-down approach [25]. Another study ascertained reference values from 24 statistically-based dwelling archetypes, representative of the EU housing stock, and found that dwellings typically contribute 6.36 tCO_{2eq}/yr (covering modules A1-A5, B4, B6, C1-C4) when considering a 100-year building lifetime [26]. In 2016, in France, an LCA-based labelling scheme 'energie positive and réduction carbone (E+C-)' was established and later guidance values were identified from 40 low-energy houses at 8.4 $kgCO_{2eq}/m^2/yr$ given a 50-year building lifetime [27]. Similarly, the Swedish Green Building Council is developing a benchmarking tool for residential buildings. Early indications already show a benchmark level between 220-262 $kgCO_{2eq}/m^2$ which equates to 3.6-4.4 $kgCO_{2eq}/m^2/yr$ when considering a 60-year building lifetime. From 2022, Sweden will require the use of environmental product declarations (EPD) for all new buildings, excluding single-family homes [28]. Denmark has developed benchmark GHG emission values based on 7 residential buildings (A1-A3, B4, B6, C3-C4) of which 6 $kgCO_{2eq}/m^2/yr$ are embodied emissions and 2.17 $kgCO_{2eq}/m^2/yr$ are operational emissions, based on a

120-year building lifetime [10]. Italy has also developed benchmark GHG emission values based on 28 residential buildings (A1-A5, B4, B6, B7, C2-C4) of which 3.8 $kgCO_{2eq}/m^2/yr$ are embodied emissions and 10.4 $kgCO_{2eq}/m^2/yr$ are operational emissions, based on a 100-year building lifetime, and using natural gas for heating [10]. GHG emissions from New Zealand residential and office buildings need to be reduced by at least 67% to operate within their shares of the global carbon budget, whereby New Zealand detached residential buildings have a climate target of 71 tCO_{2eq} over a 90-year lifetime [29]. One previous study reviewed LCA results of 95 residential buildings and found total embodied emissions for buildings ranged between 3.0 – 17.5 $kgCO_{2eq}/m^2/yr$ (adjusted for a 60-year building lifetime) [30]. Another study reviewed 200 buildings and found total embodied emissions ranged between 4.2 - 11.7 $kgCO_{2eq}/m^2/yr$ [31]. The study also found that healthcare buildings have typically higher embodied emissions and that hotels have similar embodied emissions to residential buildings [31]. Another study systematically reviews 650 LCA studies and finds embodied emissions are escalating as buildings become more energy efficient [32]. The Czech Republic combine a top-down and bottom-up approach to obtain climate goals in accordance with the Paris Agreement, and found that the bottom-up analysis exceeds the top-down goal by a factor of 2.5 [33]. The Norwegian Green Building Council is also working towards 'Paris proof buildings' in BREEAM-NOR, and defines it as a building that uses materials with low CO_2 emissions from production and transport, low operational energy use, uses renewable energy sources, has a fossil or rather emission-free construction site and facilitates for public and fossil or rather emission-free transport [34].

3. Method

LCA is an established methodology for assessing the environmental performance of buildings [9, 35-37]. The methodology used in this paper, involves collecting empirical life cycle GHG emission results from Norwegian building case studies sampled from Futurebuilt [5, 38], Framtidens Byer and Framtidens Bygg [39], the zero emission building (ZEB) research centre [40] and the ZEN Research Centre's industry partners [11]. A meta-analysis has been carried out for a total of 133 Norwegian building cases, which have been collected from 2009-2020, covering in total 1,023,738m^2 of heated floor area for 49,360 building users. Some of the cases are variations of the same building, however, using different sets of data. Each case study has calculated embodied GHG emission results in either Simapro [41], klimagassregnskap.no (KGR, a precursor to OneClick LCA) [42], OneClick LCA [43] or the MS Excel-based ZEB tool for GHG emission calculations developed by the ZEB Research Centre [44], all of which follow to some degree the LCA methodology outlined in [9, 36, 37]. All studies have the same functional unit, but the gathered data has not been further harmonised, which may lead to a variation in results due to varying practices and tools used. The data has then been used to perform a statistical analysis to provide bottom-up derived reference values, with minimum values, maximum values, 5th, 25th, 75th and 95th percentiles, as well as mean and median values. In the forthcoming ISO 21678, a limit value is defined as the lowest value of acceptable performance, and in this study that is the 75th percentile; the reference value is defined as state-of-the-art or business as usual, in this study this is the median value; whilst the target value represents the upper limit of the scale of what is theoretically possible, in this case the 5th percentile. Building typologies include 1 library, 4 museums, 15 nurseries (kindergartens), 6 nursing homes, 25 offices, 37 residential buildings, 39 schools, 2 swimming pools, 3 sports halls, 1 hotel and 1 neighbourhood, of which 14 cases are refurbishment projects. GHG emission results are reported, where available, in terms of project phases (i.e. reference, design and as-built), per life cycle module and per building part according to NS 3720 and NS 3451 [9, 45]. Tests were performed to determine if the difference between the means of the project phases, as well as between building typologies, were statistically significant. Other important data, available to various degrees for each case, includes location, year, GHG emission calculation tool used, building typology (according to [46]), number of users, number of floors, and floor areas: gross floor area, built-up area, heated floor area and net floor area according to NS 3940. Embodied GHG emissions are reported in terms of global warming potential (GWP) impacts with a functional unit of '1m^2 of heated floor area over a building lifetime of

60 years' ($kgCO_{2eq}/m^2/yr$). A preliminary screening of the LCA results has allowed the authors to narrow the scope of this research to life cycle modules A1-A3 and B4.

4. Results

Figure 1 shows the embodied material emissions (A1-A3, B4) for 59 case studies that reported data for the as-built phase. The figure also illustrates which calculation tools have been used over time, according to methodological development, and the temporal introduction of new standards and calculation tools. and the development of calculation tools. The results show a decrease in emissions from 2012/13 at the time in which EN15804 and EN15978 are introduced, as well as klimagassregnskap.no v.4 with an improved emission factor database and the introduction of the ZEB tool. This result is likely a result of the introduction of more standardised data sources from for example environmental product declarations (EPDs) and the Ecoinvent database. It will be interesting to see what influence the introduction of NS3720 and the current wide-spread use of OneClick LCA since 2018 will have on future life cycle GHG emission calculations and results in Norway. The German EPD foundation, IBU, has also observed that selecting products with EPDs have a positive impact on the ecological footprint of a building [47]. Figure 1 presents two anomalies of high embodied emissions compared to the other case studies. The first case did not optimise material emissions during the design process and incorporated large amounts of exposed concrete to utilise its thermal mass properties. The other case included a detailed material inventory of all technical equipment, thus leading to higher embodied emissions from technical equipment. Renovation projects (pink) have significantly lower emissions compared to new buildings.

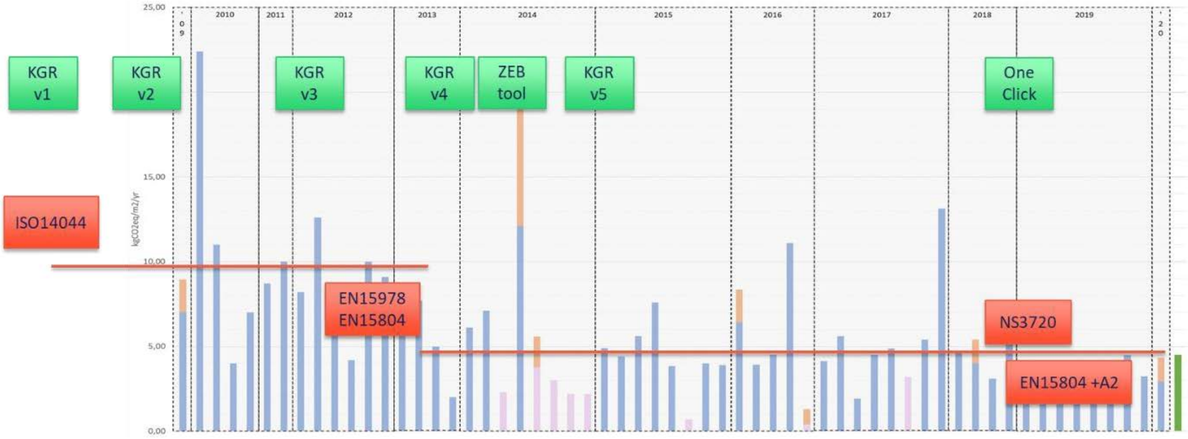

Figure 1: Embodied GHG emissions for life cycle modules A1-A3 (blue) and B4 (orange) in the as built phase in chronological order. All case studies from Futurebuilt have aggregated embodied material emissions into one score (blue). Renovation projects are shown in pink. The average for all cases is shown in green.

Figure 2 presents the statistical results from the building case studies grouped by project phases (reference, design and as-built) for all buildings and by building typologies that had more than ten cases, in addition to refurbishments. When excluding refurbishments, the reduction between the reference, design and as built phases are all statistically significant ($p \leq 0.005$, paired t-tests), while the difference between the means of building types is not significant ($p \geq 0.47$, t-tests, and $p=0.89$, ANOVA). These results indicate that benchmark values should be harvested from statistical results for design or as-built project phases, and with all buildings as empirical basis. Later, when a larger population of cases are available, one could use benchmark values for different building typologies, if the data value differences are statistically significant. The results show an interquartile range of 240-492 $kgCO_{2eq}/m^2$ or 4-8.2 $kgCO_{2eq}/m^2/yr$, a median of 396 $kgCO_{2eq}/m^2$ or 6.6 $kgCO_{2eq}/m^2/yr$ and a mean of 324 $kgCO_{2eq}/m^2$ or 6 $kgCO_{2eq}/m^2/yr$ for all building typologies in the as built phase. There are major outliers in the higher end of the distribution, since the median is lower than the mean. This points to using the median instead of the mean as a reference value. The results show significantly lower embodied emissions from refurbishment projects ($p<0.007$, t-tests) since load-bearing materials are not replaced. It was observed that all nursery cases are of a similar size, with timber construction, and built to passive house standards. Thus, there is less variation in the statistical analysis of nursery buildings.

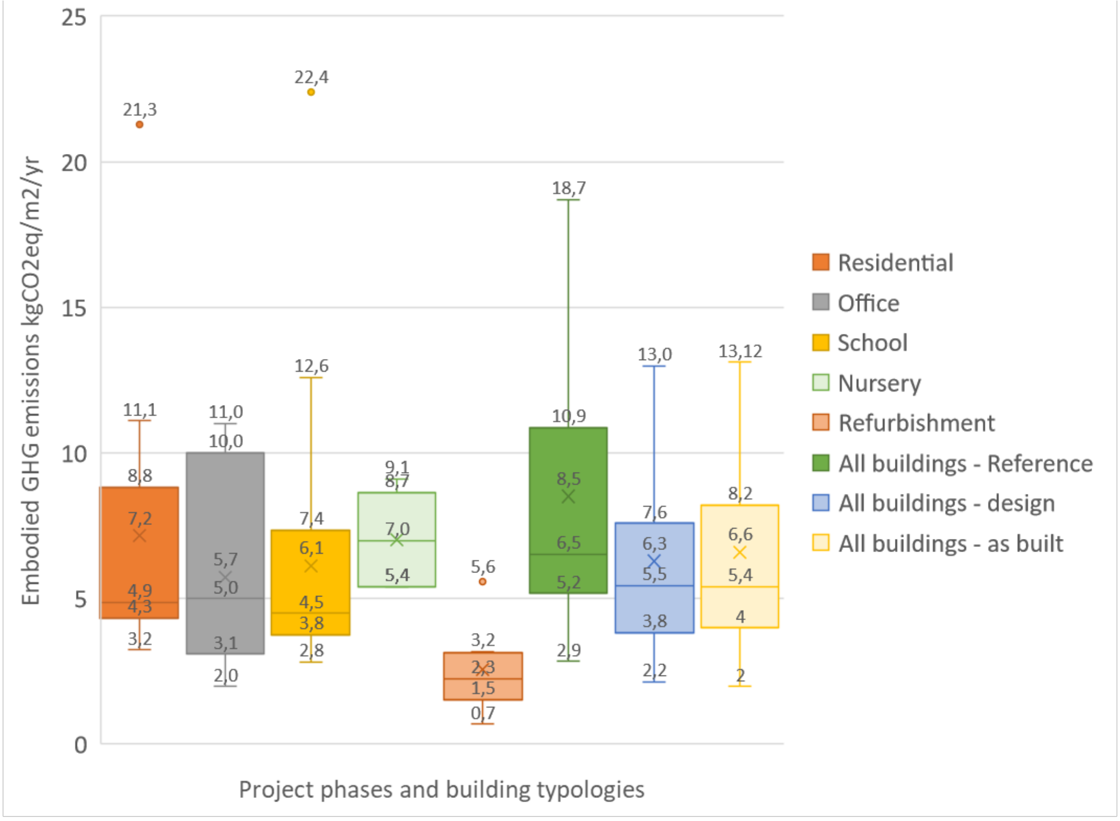

Figure 2: Boxplot of embodied GHG emissions across different project phases and building typologies (A1-A3, B4).

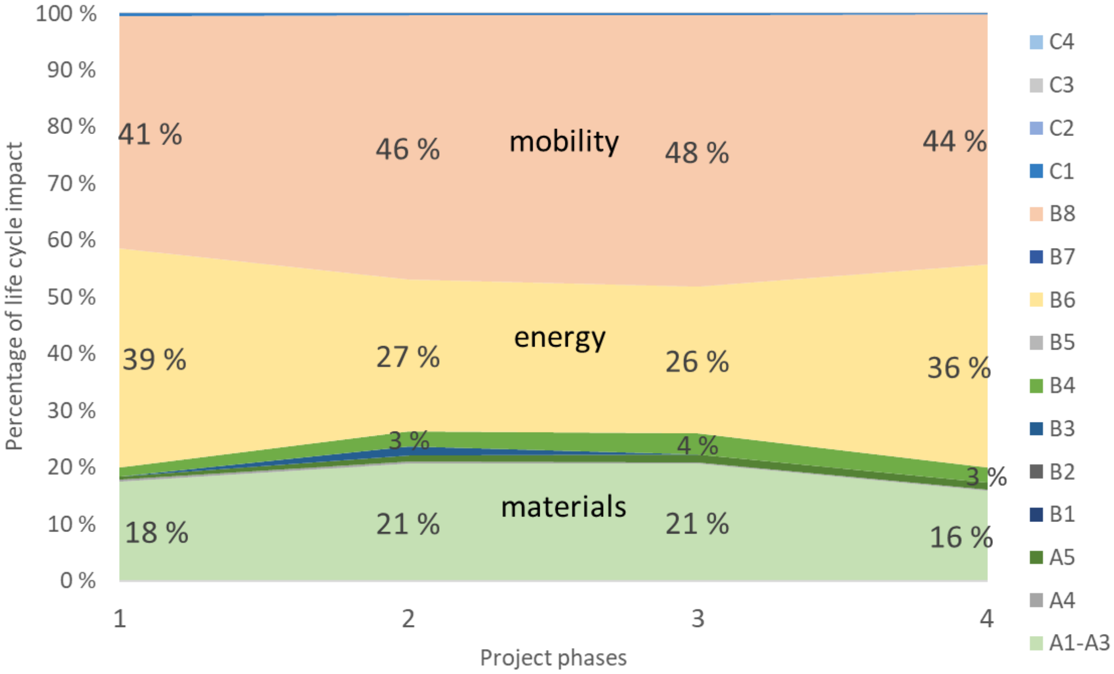

Figure 3: Life cycle total impact (A1-C4) across project phases, whereby 1) reference, 2) design 3) as-built and 4) in-use phase.

Figure 3 shows the life cycle impacts from A1-C4 across project phases and confirms there is a lower share of impacts from life cycle modules B1-B4 and C. However, these modules are typically underreported in Norwegian building LCAs. A4-A5 emissions are only now beginning to be documented in the design and as-built phases. Arguably, production phase emissions occur today and are more important for emission reduction targets. The proportion of embodied material emissions (A1-A3, B4) is fairly constant across project phases (ca. 25%), whilst the proportion of operational energy emissions (B6) are estimated high in the reference phase (39%), predicted at a reduced proportion in the design and as-built phases (ca. 26%), and rise slightly when measured in the operational phase (36%). The proportion of operational transport emissions i.e. transport activity of building users over its lifetime (B8), increases across the project phases (from 41-48%).

5. Discussion

Buildings are by nature complex products for LCA involving often thousands of processes. This is challenging as many variables need to be harmonised to establish benchmarks; for example building design parameters such as typology, context, location, climate, function, design, technology, materials and stakeholders, as well as methodological considerations such as system boundaries, scenarios, background data, inventory completeness, functional unit, reference study period, reference service lifetimes, electricity mix, definition of area, data quality, and LCI databases. However, in reality, building designs will vary and LCAs will be carried out by different stakeholders, so any proposed benchmarks should consider this to be robust. It is preferable to set benchmarks at the whole building level since CO_{2eq} emission requirements set at the material production level only do not account for consumed material quantities or the function of materials in terms of the building context. One suggestion involves using the results of this study to form environmental performance classes e.g. A, B, C, D, E whereby E corresponds to the limit value (75th percentile), C to the reference value (median) and A to the target value (5th percentile). Benchmark values may allow professionals to compare and optimise their projects relative to current common practice and encourages no single solution for optimised environmental performance. The results are in line with the benchmark values observed in IEA EBC Annex 57, ranging from 4-8.2 $kgCO_{2eq}/m^2/yr$ in the as built phase. For refurbishment projects our (Norwegian) results are slightly lower (2.3 $kgCO_{2eq}/m^2/yr$), for office buildings our range is slightly wider (3.1-10 $kgCO_{2eq}/m^2/yr$), for residential buildings our results are slightly higher (4.3-8.8 $kgCO_{2eq}/m^2/yr$) whilst for school buildings our results have a slightly narrower range (3.8-7.4 $kgCO_{2eq}/m^2/yr$). The reasons for these differences are unclear and require further study. There is also a need for validating, and harmonising details in the approaches and methodologies across the 133 Norwegian cases.

This study presents the largest known survey to date of embodied GHG emissions from Norwegian buildings. In Norway, there are 4.2M buildings (covering 5490 km^2 of developed land (this study covers 0.02%)), of which 1.5M are residential, 39,000 office and 48,000 school buildings. Norway has a population of 5.3 million (this study covers 0.9%). The gathered LCA studies are detailed, and contain data collected by third parties that was available at the time of the study. The database may be too small a sample to draw robust conclusions on a national level. The study is also subject to convenience and may represent extreme sampling, since the cases are the ones we happened to gain access to, and they are exemplary buildings from programmes such as Futurebuilt and the ZEB Research Centre that strive for reduced energy and low material and transport emissions, and they document this through LCAs, which is not yet common practice in Norway. However, we assume that results for the reference project phase are more representative of business as usual, whilst the design and as-built phases show the potential of what is possible to achieve today. However, the various project phases are subject to data quality and availability (e.g. material quantities) at the time calculations were carried out.

The results from such a bottom-up approach are subject to variability due to technological differences across cases, also over time. Resch et al. introduce the concept of technological improvement factors for future emission reductions in material production and transport [48]. Technological improvements can arise from material, production and transport technology, recycling rate, prefabrication, automation, the electrification of processes and the decarbonisation of the electricity grid. Here, technological vectors are modelled as linear decreases, 50% lower for production and 90% lower from transport in 60 years [49]. These factors may be applied to future development of CO_2 emission requirements and benchmark values instead of or as well as relying on a large sample of case studies. Scope for further work may also include recalculating benchmark values when a larger body of LCAs are available so that benchmarks can be developed for different building typologies, expanding the study to more life cycle modules so that benchmarks can be developed for the whole life cycle, and combining the results from this study with a top-down approach to develop performance targets in accordance with the Paris Agreement.

6. Conclusion

The results of this research are useful to help form initial indications for GHG emission requirements and benchmark values in Norway and may be used in either future Norwegian building codes (e.g. TEK20), by Futurebuilt and as benchmark values applicable in the ZEN Research Centre. Statistical significance test results indicate no statistical difference between building typologies, on the basis of a population of 133 cases, and that one should use emission data from the design or as-built project phases of buildings.

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