Low-Carbon Building Design in Danish Method and Practice

assessing and lowering life cycle greenhouse gas emissions from residential buildings

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BY
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DISSERTATION SUBMITTED 2019

AALBORG UNIVERSITY
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ENGLISH SUMMARY

As the climate crisis unfolds, the sustainability agenda is gaining full attention by citizens, companies, institutions, politicians, and decision-makers in general. Current policies set targets for European and national-level net zero greenhouse gas emissions from human activities by the year 2050. This ambitious goal requires an urgent, dedicated and hitherto unparalleled engagement in all spheres of human activity. The building sector is responsible for a large share of global greenhouse gas (GHG) emissions and consumes vast amounts of resources and energy. Thus, within the next thirty years, the building and construction activities must undergo a radical transformation.

Identifying and using effective design strategies are pivotal for reducing operational and embodied GHG emissions from buildings. In this dissertation, I provide the Danish building sector with benchmarks and emission profiles of state-of-the-art design strategies for low levels of embodied greenhouse gas emissions, popularly termed embodied carbon. This dissertation also unveils how the sectoral context affects the method and the results of life cycle carbon footprint of buildings. Lastly, the dissertation critically evaluates the current assessment practice as well as the low-carbon strategies in relation to the net zero targets.

Five design strategies, mirroring common building practice, were evaluated in terms of embodied carbon: *Recycling* proved to be an effective design strategy for low-carbon housing with a saving potential for embodied carbon of around 40% compared to a typical single-family building. Designing for a *long service life of building materials* yielded saving potentials within the same range, although this potential is much dependent of the set scenarios. The example of *design for adaptability* entailed a lesser saving potential in a life cycle perspective and was much dependent on the modelled scenarios. There may be life cycle carbon benefits in a strategy about *designing for low energy consumption*, although the projected development towards a decarbonised energy system greatly influences these potential benefits. A *design for disassembly* in a terraced house resulted in an increase of embodied carbon compared to the reference, although there may be benefits in a wider systems perspective outside the single product-chain. Additional strategies, e.g. concerning bio-based and less processed materials, as well as combination potentials between the strategies should be further investigated to support the carbon reduction targets.

From a benchmark study of average, Danish multi-family and single-family buildings, the median embodied carbon profile was found to be 6.0 kg CO_2e/m^2/year over a 120-year reference study period. However, keeping the

urgency for rapid transition of the building sector in mind, a 120-year perspective is utterly inadequate for effectively dealing with today's emissions. Thus, benchmarking methods are recommended to focus more on reducing the current emissions from production and construction, and evaluating these in relation to the remaining budgets for CO_2 emissions. Furthermore, there is a need for rigid rules-in-practice within specific contexts, e.g. concerning the use of database and choice of scenarios.

In the research of contextual influence, the validity and efficiency of the above mentioned strategies and benchmarking methods are put in perspective. In an analysis of the life cycle assessment (LCA) and benchmarking practice, I show how the method is shaped within a broad constellation of actors and contextual preconditions. The resulting assessments, and the benchmark system itself, is broadly accepted within the sector. Nonetheless, it also contains a range of identified, methodological trade-offs that may counteract general principles of, for instance, comprehensiveness. Hence, the method applied in practice needs continuous development to support the emission reduction targets in a more accurate manner.

To further clarify the importance of methodological choices, I present a systematic mapping of the method-related drivers for results obtained from LCA of buildings. I pinpoint the methodological settings that building professionals and researchers need to consider in the use of and further practice-oriented development of methods and specific initiatives for low-carbon building design.

Based on a critical discussion, I present a framework for understanding the dynamic relations between low-carbon design strategies and the evolving method by which the strategies are assessed in Denmark. Current practice, i.e. how buildings are built and how LCAs are carried out, constitute the centre of the framework. A low-carbon built environment is progressing in an interaction between the specific initiatives and the method/data/tools used for assessing the environmental viability of these initiatives. The initiatives, the method/data/tools as well as the practice is shaped by the sectoral context, i.e. the regulation, standards and trends characterising the focus of the national building sector. The sectoral context itself is influenced by the surrounding societal context, i.e. bordering regulations, trends and targets. The changes of context, e.g. the introduction of net zero targets, necessitate reconfiguration of the practice for building design as well as for the methods/data/tools used for carbon assessments.

According to the research presented in this dissertation, current low-carbon building practice is a mere step on the way towards a building sector in sync with the planetary boundaries for GHG emissions, and the development of design strategies as well as carbon assessment methods must be stepped up intensely in the forthcoming years.

DANSK RESUME

Bæredygtighedsagendaen har opnået fornyet fokus i den offentlige debat, især set i lyset af en truende klimakrise. Nyere politiske mål, både på europæisk og på nationalt niveau, sigter mod CO_2-neutralitet, dvs. netto-nul udledninger af drivhusgasser i år 2050. Byggesektoren er ansvarlig for en stor del af de globale drivhusgasudledninger og har et højt forbrug af ressourcer og energi. Dermed er en radikal transformation af gældende praksis i byggebranchen bydende nødvendig inden for de næste 30 år.

Det er overordentlig vigtigt at få reduceret driftsrelaterede og indlejrede emissioner i det byggede miljø, og det kræver at der identificereres og implementeres effektive bygningsdesigns med et lavt niveau af drivhusgasudledninger, såkaldt lav-emissionsbyggeri. Fokus for forskningen i denne afhandling er at bibringe den danske byggesektor en række emissionsprofiler fra udvalgte designstrategier med fokus på lave niveauer af indlejrede drivhusgasemissioner. Denne forskning afklarer samtidig hvordan byggesektorens kontekst påvirker metoden og resultaterne af de livscyklusvurderinger (LCA) der udarbejdes på bygninger for at fastslå klimabelastningen. Slutteligt bidrager afhandlingen med en kritik af den aktuelle vurderingsmetode og af de designstrategier der er i spil i praksis.

I denne afhandling er fem udvalgte designstrategier fra byggepraksis evalueret med hensyn til indlejrede drivhusgasemissioner. *Genanvendelse* viste sig at være en effektiv designstrategi for nye lav-emissionsboliger med et besparelsespotentiale på omkring 40% sammenlignet med en referencebygning. Design med henblik på en *lang levetid for byggematerialerne* gav et besparelsespotentiale på førnævnte niveau, men dette potentiale er meget afhængigt af de scenarier der defineres for hyppigheden af udskiftninger. Eksemplet med *fleksibelt, modulært design* medførte et mindre besparelsespotentiale i et livscyklusperspektiv og var ligeledes meget afhængig af de definerede scenarier for tilpasninger af huset. Der kan være fordele angående lav-emissioner i en designstrategi møntet på *lavt energiforbrug*, skønt den modellerede dekarbonisering af energisystemet i høj grad påvirker disse potentielle fordele. Et *design for adskillelse* (design for disassembly – DfD) i et rækkehus viste sig at medføre en stigning i indlejrede emissioner sammenlignet med referencebyggeriet, omend der kan være fordele ved DfD-designet i et større systemperspektiv. Strategierne vurderet i denne forskning begrænser sig til at være en række eksempler fra praksis. Yderligere strategier bør undersøges, fx vedrørende brug af bio- og lav-forarbejdede materialer. Kombinationspotentialerne af strategierne bør også undersøges med henblik på at imødekomme målene for reduktion af drivhusgasser.

Denne forskning identificerer et foreløbigt referenceniveau for indlejrede drivhusgasser fra danskboligbyggeri. Dette referenceniveau ligger på 6,0 kg CO_2e/m^2/år over en 120-årig levetidsbetragtning. Et 120-årigt perspektiv er dog utilstrækkeligt med henblik på retvisende at håndtere nutidige emissioner fra produktion og konstruktion. Samtidig bør emissionerne fra byggeriet i højere grad vurderes op imod det tilbageværende budget for emissioner på globalt plan. Derudover er der brug for faste regler for vurderingen af bygningers emissioner, f.eks. vedrørende valget af database og scenarier for modelleringen.

Afhandlingen præsenterer desuden en perspektivering af ovennævnte strategier og metoders validitet. I en analyse af praksis for livscyklusvurdering (LCA) og benchmarking viser jeg hvordan metoden formes i en bred konstellation af interessenter og forudsætninger. Den resulterende metode er bredt accepteret og benyttet i branchen. Ikke desto mindre indebærer løsningen også en række metodiske trade-offs vedrørende de generelle LCA-principper om, f.eks. fuldstændighed og repræsentativitet. Metoden der benyttes i praksis bør dermed udvikles løbende for, mere præcist, at bakke op om reduktionsmålene.

I en yderligere klarlægning af betydningen af metode, præsenterer jeg i afhandlingen en systematisk kortlægning af de metode-relaterede valg der foretages ved en bygningsLCA. Jeg indkredser de metodiske valg som professionelle og forskere skal tage med i overvejelserne angående udviklingen af fremtidige initiativer vedrørende lav-emissionsbyggeri.

Baseret på en kritisk diskussion af resultaterne bibringer denne afhandling en ramme for forståelse af forholdet mellem strategier til lav-emissionsbyggeri og den LCA-tilgang hvormed strategierne vurderes. Den konceptuelle ramme fremhæver ligeledes de omgivende forhold og kontekster der påvirker hvordan lav-emissionsstrategier udføres i metode og praksis. Heraf følger at den fremtidige indsats hen imod netto-nul emissioner for byggeriet bør tilpasses så konkrete, byggede initiativer samt LCA-metodeudvikling foretages under hensyn til praksis, men også under hensyn til strømninger og forhold i både byggesektoren samt samfundet som helhed.

Af afhandlingens resultater fremgår det hvorledes den nuværende praksis for lav-emissionsbyggeri er et mindre skridt på vejen mod en CO_2-neutral fremtid, og både designstrategier samt vurderingsmetoder bør videreudvikles intensivt i de kommende år.

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PREFACE

This dissertation is the result of a PhD project carried out from 2015 to 2019 at the Danish Building Research Institute, Aalborg University. The core collection of publications for this dissertation consists of the four mentioned in Chapter 1. Their common focus is on low-carbon design strategies in Danish method and practice. Complementing the four core publications is a diverse set of other, related publications elaborated during the course of the PhD project. These additional publications shed light on topics that, in different ways, put perspective on the core set of publications. The complementing publications are as follows:

Topic: LCA practice, method and tool development in the Danish context

- “Holistic sustainability: Advancing interdisciplinary building design through tools and data in Denmark”. Sørensen, Nils Lykke; Rasmussen, Freja Nygaard; Øien, Turid Borgestrand; Frandsen, Anne Kathrine. *Accepted for publication in Construction Economics and Building, 2019*
- ”Development of LCAbyg: A National Life Cycle Assessment Tool for Buildings in Denmark”. Birgisdóttir, Harpa; Rasmussen, Freja Nygaard. *Published in IOP Conf. Series: Earth and Environmental Science, 2019*
- ”Development of the LCAbyg tool: influence of user requirements and context”. Rasmussen, Freja Nygaard; Birgisdóttir, Harpa. *Published in the proceedings of the SBE16 Hamburg conference, 2016*

Topic: GHG emissions from buildings and design strategies for reductions

- ”Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation”; Röck, Martin; Saade, Marcella; Balouktsi, Maria; Rasmussen, Freja Nygaard; Birgisdóttir, Harpa; Frischknecht, Rolf; Habert, Guillaume; Lützkendorf, Thomas; Passer, Alexander; *Published in Applied Energy, 2020*
- ”Design and construction strategies for reducing embodied impacts from buildings – Case study analysis”; Malmqvist, Tove; Nehasilova, Marie; Moncaster, Alice; Birgisdóttir, Harpa; Rasmussen, Freja Nygaard; Houlihan Wiberg, Aoife; Potting, José; *Published in Energy and Buildings, 2018*

Topic: LCA benchmarking – examples of relative and absolute approaches

- ”Life cycle assessment benchmarks for Danish office buildings”; Rasmussen, Freja Nygaard; Birgisdóttir, Harpa; *Published in Proceedings*

of the Sixth International Symposium on Life-Cycle Civil Engineering – IALCCE, 2018
- ”Assessment of absolute sustainability in the built environment” Andersen, Camilla; Ohms, Pernille; Birgisdóttir, Harpa; Birkved, Morten; Hauschild, Michael; Ryberg, Morten. *Submitted to Building and Environment, 2019*

Topic: Circular economy in the building sector

- ”Circular building materials: Carbon saving potential and the role of business model innovation and public policy”. Nußholz, Julia; Rasmussen, Freja Nygaard; Milios, Leonidas. *Published in Resources, Conservation and Recycling, 2019*
- “Circularity in the built environment – a call for a paradigm shift”. Malmqvist, Tove; Rasmussen, Freja Nygaard; Moncaster, Alice; Birgisdóttir, Harpa. *Book chapter accepted for publication in Handbook of the Circular Economy edited by Brandão, M.; Lazarevic, D.; Finnveden, G; forthcoming 2020*

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GLOSSARY

BIM	Building Information Model
BREEAM	Building certification system (Building Research Establishment Environmental Assessment Method)
CEN	The European Committee for Standardization (Comité Européen de Normalisation)
CO_2e	CO_2 equivalents
DfD	Design for Disassembly
DGNB	Building certification system (Deutsche Gesellschaft für Nachhaltiges Bauen)
EN 15978	European standard: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method
EN 15804	European standard: Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products
EoL	End-of-Life
EPD	Environmental product declaration
GHG	Greenhouse gas
GWP	Global warming potential
IEA	International Energy Agency
IEA-EBC	International Energy Agency's Energy in Buildings and Communities Programme
IPCC	Intergovernmental Panel on Climate Change
ILCD	International Life Cycle Data system
ISO 2193	International standard: Sustainability in buildings and civil engineering works - Core rules for environmental declaration of construction products and services used in any type of construction works
ISO/TS 21931-1	International standard technical specification: Sustainability in building construction – Framework for methods of assessment for environmental performance of construction works – Part 1: BuildingsLCA: Life Cycle Assessment
LCA	Life cycle assessment
LCI	Life cycle inventory
LEED	Building certification system (Leadership in Energy and Environmental Design)
PCR	Product category rules
PEF	Product Environmental Footprint
RSP	Reference study period
UN	United Nations
ZEB	Zero emission (or energy) building

CHAPTER 1. INTRODUCTION

CLIMATE CHALLENGES OF THE BUILDING SECTOR

In recent years, the sustainability agenda concerning environmental impacts and resource uses has gained traction in the public sphere of interest. Specifically, the concerns about climate change has evoked action, e.g. from the young generation's Fridays for Future strikes and demand for political action, now. In the recent Danish 2019 national election, climate was high on the agenda of the voters' concerns.

The atmospheric content of greenhouse gasses (GHG) has now risen to more than 410 ppm CO_2 from a level of 280 ppm at pre-industrial times (NASA, 2019; NOAA, 2013). These higher atmospheric levels of heat-trapping greenhouse gasses from human activities have induced a global rise in temperature between 0.8 °C and 1.2 °C (Masson-Delmotte et al., 2018). In 2016, leading politicians from around the world signed the Paris-agreement, stating ambitions for implementing political actions that would constrain the global temperature rise at a level of maximum 2 °C above pre-industrial levels. However, in 2018, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations issued further warnings about the consequences of a +2 °C future, stating that even +1.5 °C would bring about fundamental changes of the global ecosystems (Masson-Delmotte et al., 2018). The IPCC report stated that not only does society need to speed up with lowering the current level of GHG emissions. It also stated that to avoid a climate crisis, all anthropogenic activities must come to a level of net zero GHG emissions by year 2050 (ibid). Recent communications from policy bodies support this target: The new European Commission (assuming office in late 2019) has outlined the so-called European Green Deal that involves enshrining the "…2050 climate-neutrality target into law" (Von der Leyen, 2019). The Danish government further voiced a milestone on the way to 2050 by aiming for 70% GHG emissions reductions from national activities by 2030 (Ministry of Higher Education and Science, 2019).

The task is overwhelming and requires careful coordination between sectors. For buildings, the specific contributions have to do with emissions from energy for heating, cooling and appliances and from the process-specific emissions related to the production, construction, maintenance, and waste treatment of the building materials – the so-called embodied emissions (see e.g. Balouktsi & Lützkendorf, 2016). On a European level, the energy used for building operation amounts to 36 % of the final energy use and emissions (European Parliament, 2018). On a global level, the International Energy Agency states that 11 % of all GHG emissions originate from the production of materials for construction and renovation of buildings (IEA, 2019).

On a national level, the Danish building sector is increasingly committing its practice towards a sustainability agenda. In the past decade, several initiatives concerning development of certification systems (e.g. the DGNB certification system) and implementation of sustainability strategies (e.g. governmental strategy for circular economy) have paved the way for a more dedicated approach for the entire sector. However, the ambitious reduction targets require a focused effort from the sector as well as a standardised assessment of the actual emissions and the saving potentials achievable by a change of practice.

For decades, environmental life cycle assessment (LCA) has been the prevalent method of documenting the GHG emissions profile, also known as the ‘carbon footprint’ of products and services (Laurent, Olsen, & Hauschild, 2012). Although the general LCA method is harmonised by common standards such as the ISO 14040-14044 (ISO, 2006a, 2006b) and the EN 15804 (CEN, 2012a), the LCAs applied in practice still vary widely in composition and resulting conclusions (Birgisdóttir et al., 2016; Röck et al., 2020). A key aspect in this regard relates to the way in which assessors (e.g. architects or engineers) interpret the standards and define the suitable scope for the specific investigation (De Wolf, Pomponi, & Moncaster, 2017). These background variations of the applied method may cause large variations in results. Hence, to an LCA layperson, i.e. the average GHG-attentive building designer, it is extremely difficult to pinpoint the effective strategies and emission drivers, because they may differ from one assessment context to the other.

RESEARCH AIM, -FOCUS AND –QUESTIONS

The transition of the built environment towards ambitious emission reduction targets requires an identification and implementation of effective low-carbon design strategies in the built environment. Additionally, the method- and practice-related drivers of variations in results need a systematic investigation.

‘Carbon’ is in the remainder of the dissertation used as the popular term denoting GHG emissions.

The aim of this dissertation is to provide the Danish building sector with the life cycle embodied GHG profiles of low-carbon design strategies applied in practice. Further, the dissertation aims to clarify, for the building sector, how the assessment method affects the LCAs carried out and how the method may be adjusted to align with the overall targets on net zero carbon emissions.

The dissertation has a dual focus on the assessment method and the design strategies employed under Danish conditions. In this sense, the dissertation analyses the life cycle greenhouse gas emissions associated with different design strategies for new residential buildings in Denmark. For these analyses of design strategies, LCA has been employed as the primary method. Additionally, the dissertation critically analyses the differing methodological settings in which the LCA method for buildings is operated in Denmark, and evaluates how these methodological choices differ due to context specific preconditions.

The overall research question of the dissertation is:

- How do selected low-carbon design strategies contribute to solving the climate challenge of the building sector when evaluated according to Danish assessment practice?

Four sub questions pertain to the main research question:

  - What is the embodied carbon in examples of design strategies applied in the Danish building practice?
  - What is the level of reference for the embodied carbon of new residential buildings in Denmark?
  - How does the Danish assessment practice for building LCAs align with general principles of LCA
  - Which method-related drivers affect the outcome of building LCAs?

READER'S GUIDE

The research questions of this dissertation are addressed through the analytical work presented in a selection of four academic publications:

Publication I: **Low-carbon design strategies for new residential buildings – lessons from Danish architectural practice.** *Rasmussen, F; Birkved, M; Birgisdóttir, H.* Submitted to Architectural Engineering and Design Management, 2020

Publication II: **Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies.** *Rasmussen, F; Birkved, M; Birgisdóttir, H.* In: IOP Conference Series: Earth and Environmental Science, 2019 (225)

Publication III: **LCA benchmarks for residential buildings in Northern Italy and Denmark – learnings from comparing two different contexts.**

Rasmussen, F; Ganassali, S; Zimmermann, R; Lavagna, M; Campioli, A; Birgisdóttir, H. In: Building Research and Information, 2019 (47) 7 pp 833-849

Publication IV: **Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings.** *Rasmussen, F; Malmqvist, T; Moncaster, A; Houlihan Wiberg, A; Birgisdóttir, H.* In: Energy and Buildings, 2018 (158) pp 1487-1498

The research of this dissertation is set within the dynamic and practice-related development of method as well as actual initiatives. Figure 1 illustrates graphically how the publications are connected to the core topics of the dissertation. Publication I contains an analysis of four low-carbon design strategies applied to a sample of five buildings erected as part of an experimental project. The four design strategies of Publication I concern 1) upcycling/recycling of materials, 2) prolonged service life of materials and components, 3) design for adaptability, 4) design for low operational energy. Publication II evaluates the design strategies of upcycling/recycling and design for disassembly, and furthermore clarifies the influence of allocation method on this assessment. Publications III and IV deal with the effect of LCA method and practice on the results obtained in building LCAs. Publication III furthermore derives a set of preliminary benchmarks for residential buildings. These benchmarks are used to cross validate the results of the low-carbon strategies addressed in publications I and II.

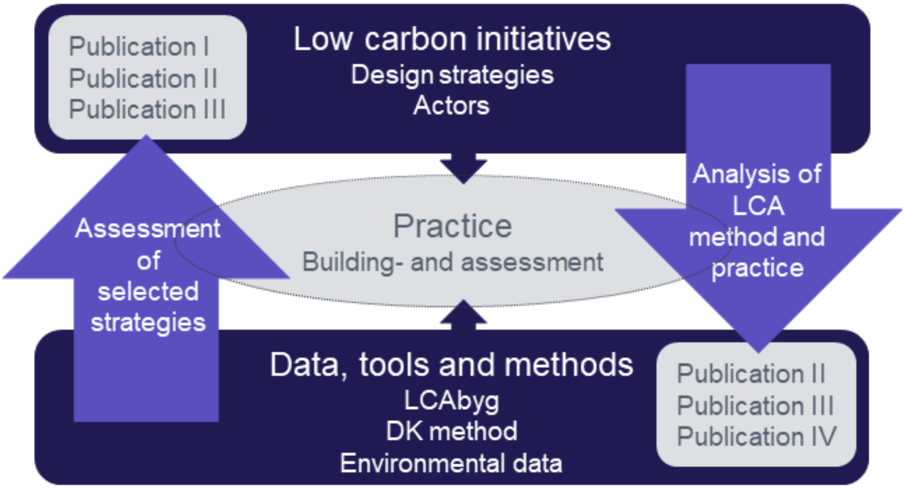

Figure 1. Illustration of the topics and linkages between the publications of the dissertation

The following chapters of this dissertation outline first, in Chapter 2, the state of the art regarding LCA and design strategies in the building sector. Chapter 3 details the methods in use within the publications. Chapter 4 presents the results from the research work in relation to the two topics of Figure 1, i.e. the assessment of selected strategies as well as the analysis of LCA method and practice. Chapter 5 introduces additional outlooks as part of a discussion to put perspective on the conclusions of Chapter 6. Chapter 2, 4 and 5 contain summaries that allow for a quick reading of the dissertation.

The methods used for addressing the topics of the current dissertation are outlined in Table 1. This is further elaborated in Chapter 3 on Method.

Table 1. The methods applied in the different publications

Method	**Publication**			
	I	**II**	**III**	**IV**
Review				X
Case study	X	X	X	X
Life cycle assessment	X	X	X	

MAIN CONTRIBUTIONS

The main contributions originating from this dissertation can be summed up as follows:

- Comparison of the carbon profiles of five different design strategies for low-carbon building practice in Denmark

- Evaluation of the effect of the CEN standards' allocation principle on two different design cases and the timing of their environmental potentials

- Development of an intermediate set of reference LCA values for residential buildings in Denmark

- Identification of the contextual considerations and trade-offs made in assessment practice, specifically for the benchmark setting

- A structured identification of points-of-attention concerning assessment practice and transparency in the framework of the EN 15978 European standard for sustainability of construction works

- A guiding framework that highlights the dynamics of the context within which the current Danish LCA practice is founded.

- A critical reflection on how the probable net zero carbon future poses challenges to the LCA method when modelling carbon footprints from the extensive life cycle of buildings.

CHAPTER 2. STATE-OF-THE-ART

This chapter presents a general overview of state-of-the-art relevant to the research topics presented in the previous chapter. The state-of-the-art elaborates on existing concepts and relevant literature to further sum up and specify the research gaps that need addressing in the context of the current research work.

LCA IN THE BUILDING SECTOR

Life cycle assessment is a science-based method used to quantify the environmental impact potentials and the resource uses of a product or a service over its full life cycle (Bjørn, Owsianiak, Molin, & Laurent, 2018). The method has been a key assessment tool within the eco-efficiency agenda that was adopted by several institutions and companies following the UN's work on sustainable development (Wenzel, Hauschild, & Alting, 1997). The main strength of LCA as a method for environmental assessments is the fact that it includes the exchanges with the environment from the assessed product itself as well as the background systems of the whole value chain of the product. LCA is furthermore flexible in terms of the applied scope. Hence, depending on the purpose of the assessment, a broader or narrower scope can be defined, specifying the processes that constitute the system under study.

LCA as a method is standardised via the ISO 14040 and 14044 that define a harmonised terminology for the concepts in play at different levels of assessment. Although harmonising in their essence, the standards allow for widely different approaches to defining the appropriate system for a given study (Passer et al., 2015). In parallel to the standards, a growing focus on green product policies has further spurred several initiatives for calculating and declaring the life cycle based evaluations of products via the environmental product declarations (EPDs). The EPDs are used by producers and industry organisations to declare the environmental performance of their products on the market. ISO has detailed the LCA procedure for use in the EPDs for construction products with a modular approach (ISO/TC 59/SC 17, 2017) that also forms the backbone of the European Standards for LCA on construction products and for whole buildings (CEN, 2012a, 2012b). Table 2 displays the modular life cycle stages that form part of the ISO- and CEN-standardised assessments for construction products.

Table 2. The impact types, modules and stages of a building's life cycle. Based on (Balouktsi & Lützkendorf, 2016; CEN, 2012a; Dixit, Fernández-Solís, Lavy, & Culp, 2010)

Life cycle stage	Module		Type of impacts
Product stage	A1	Raw material supply	Initial embodied impacts
	A2	Transport	
	A3	Manufacturing	
Construction process stage	A4	Transport	
	A5	Construction-installation process	
Use stage	B1	Use	Recurrent embodied impacts
	B2	Maintenance	
	B3	Repair	
	B4	Replacements	
	B5	Refurbishment	
	B6	Operational energy use	Operational impacts
	B7	Operational water use	
End of life stage	C1	Deconstruction	EoL embodied impacts
	C2	Transport	
	C3	Waste processing	
	C4	Disposal	
Benefits and loads beyond the system boundary	D	Reuse, recovery & recycling potential	(reported separately)

This harmonisation of terminology, scope and indicators facilitate the comparison of different construction products and building designs. The ISO/CEN standards on construction products thereby count as the core definitions for the category rules applied for LCA of construction products. EPD program operators define further detailed requirements on calculation and communication of the EPDs via their product category rules (PCR) for specific types of products. The PCRs are typically developed in cooperation with the respective industries (Del Borghi, 2013). Passer et al. (2015) suggest that the lack of coordination between the EPD operators impairs the harmonisation of the EPDs on a European level. However, harmonisation efforts are ongoing, for instance via the Eco Platform initiative for European EDP program holders (Eco Platform, 2019).

The modular approach to LCA of construction products (see Table 2) is also a core element of the LCA of whole buildings as standardised via the European standard EN 15978. In this sense, the life cycle stages of the whole building are defined similar to the life cycle stages at the product level (similar to Table 2). And similar to the diverse interpretations of the standards at product level, the building level LCAs also vary widely in scope of life cycle stages, inventory and background data (Birgisdóttir et al., 2016). International research projects such as the IEA EBC Annex 57 (Birgisdóttir et al., 2017) and Annex 72 (Frischknecht, 2019) aim to clarify and harmonise the various approaches taken to method and scope of building LCAs.

The building sector actors and policy makers have furthermore included LCA in much of recent activities. Standardised LCA is increasingly being used as part of the existing certification schemes for sustainable buildings (Lützkendorf, 2017). Hence, assessment schemes such as LEED, BREEAM and DGNB all include partial and/or full scale LCAs of the certified buildings. LCA of buildings have furthermore gained increased awareness from regulatory bodies, especially in Europe. The Netherlands was the first country to introduce mandatory LCA declarations for new buildings (Scholten & van Ewik, 2013). Statsbygg, the Norwegian public building administration, has introduced whole building LCAs to obtain a 40% emissions reduction in their portfolio (Statsbygg, 2019). In Denmark, work in progress concerns the development of a voluntary building code that includes an LCA of the whole building (Mortensen, Kanafani, & Aggerholm, 2018). Several other countries are investigating the topic and the level of ambition, for instance Belgium, Sweden and Finland (Boverket, 2018; Frischknecht et al., 2019).

METHODOLOGICAL MATTERS IN BUILDING LCA

Following an increase in the general interest of building LCA, the matter of benchmarking buildings on horizontal levels has become a focal point for the research community. Comparing with existing cases and results is, however, not straightforward. Erlandsson and Borg (2003) argue that since every building project is unique in its location and functional qualities, the resulting LCAs are consequently not comparable. These inherent disparities between projects set aside, obstacles concerning the applied method further add to the difficulties in comparing buildings on a horizontal level. Several studies problematize the wide spread (a factor three to six) in results obtained from reviewing existing studies (Chastas, Theodosiou, & Bikas, 2016; Hammond & Jones, 2008). They explain this as being a combination of differences in, on the one hand, the physical object of the buildings themselves, and, on the other hand, the assessment practice including methodological choices (ibid.).

Literature of research gaps and methodological challenges for LCA in general consider, for instance, impact assessment characterisation methods, uncertainty of the models and modelling of rebound effects (Finkbeiner et al., 2014; Finnveden et al., 2009; Hellweg & Canals, 2014). These can be characterised as generic LCA aspects. Moving into the more defined area of building LCA, these generic LCA gaps are in the background, whereas aspects of application are emphasised. Scientific literature touch upon the choice of LCA data and the impact on results from choosing one or the other background data for calculating the environmental impact. The considerations about data refer to the deviations between competing sources of data (Martínez-Rocamora, Solís-Guzmán, & Marrero, 2016; Pomponi & Moncaster, 2018; Takano, Winter, Hughes, & Linkosalmi, 2014) and also the resulting deviations from choosing generic data versus product-specific data (EPDs) (Houlihan Wiberg, Georges, Fufa, Risholt, & Good, 2015; Lasvaux, Habert, Peuportier, & Chevalier, 2015). On a meta-level, and focusing on life cycle energy, Dixit et al. (2012; 2010), review existing literature and identify ten parameters of relevance to the results obtained from a building analysis. Table 3 synthesise these parameters.

Table 3. Method related parameters of relevance identified by Dixit et al. (2012; 2010) *(adapted)*

Parameter	**Explanation**
System boundaries	Defines the number of energy and material inputs that are considered in the calculation of embodied impacts
Method of analysis	LCAs may be conducted based on process analysis, statistical analysis, input-output analysis and hybrid analysis. The methods possess different limitations and their level of accuracy vary
Geographic location	Studies performed in different countries differ in terms of data relating to raw material quality, production processes, economy, delivered energy generation, transportation distances, energy use (fuel) in transport, and human labour
Primary and delivered energy	Operational and embodied energy must be measured in terms of primary energy consumption in order to attain consistency and to acquire the most appropriate

	environmental implications, such as greenhouse gas emissions
Age of data	Research studies based on old and current data sources could differ significantly as a result of the changing technology of manufacturing and transportation
Data source	Research studies use data that are collected using different approaches. Some studies derive their own data by calculating the emission intensity while others utilize figures calculated by other studies
Data completeness	Often, research studies do not have access to primary data sources and rely on secondary data sources that may or may not be complete
Manufacturing technology	Differing technologies of material manufacturing possess varied levels of energy consumption and emissions
Feedstock consideration	Concerning the energy and emissions embedded in the ingredients used in the process of manufacturing a material. Inclusion/exclusion of feedstock energy and emissions in LCA could cause variations in results
Temporal representation	Some studies are based on recently developed technology, and some studies consider a mix of new and old technology. The end results of such studies differ and are not consistent

In several cases, research studies investigated the significance of varying single- or selections of these methodological parameters (Aktas & Bilec, 2012; Georges, Haase, Houlihan Wiberg, Kristjansdóttir, & Risholt, 2015; Hoxha, Habert, Lasvaux, Chevalier, & Le Roy, 2017). For instance, Häfliger et al. (2017) varied the modelling choices of database, system boundary, replacement scenarios and building service life. Insulation materials, doors and windows were material categories that had large contributions to the environmental impact of the whole building, and which were sensitive to the different modelling choices (Häfliger et al., 2017). Moncaster et al. (2018) analysed the embodied carbon of a students' housing, varying a set of three methodological parameters concerning 1) the scope of the inventory, 2) the scope of the life cycle stages included and 3) the literature-based values for embodied carbon associated with key materials used in the building. The study found variations in results up to a factor 10 and thereby highlights that: "the difference in methodology, for calculations on a single building, can be higher than the impact of different design using the same methodology" (Moncaster et al., 2018).

The rigorous analyses needed to support the credibility of a building LCA contrasts with the simplified methodological approaches necessary to encourage the use of LCA in industry practice (Anand & Amor, 2017). It is generally recognised that the application of LCA in the early design stage of a building has the most prominent potential to reduce environmental impacts over the course of the building life cycle (Marsh, 2016; Meex, Hollberg, Knapen, Hildebrand, & Verbeeck, 2018; Russell-Smith, Lepech, Fruchter, & Littman, 2015). However, practitioners within the industry perceive LCA as being too laborious and time consuming (De Wolf et al., 2017; Schlanbusch et al., 2016). Hence, the need for simplification has spurred the development of guidance and tools for LCA at different levels of comprehensiveness, from simplified/screening to advanced/detailed (Lewandowska, Noskowiak, Pajchrowski, & Zarebska, 2014; Malmqvist et al., 2011; Wittstock et al., 2012).

Although a range of these simplified and advanced approaches are in fact available, De Wolf et al. (2017) report from workshops with industrial representatives from around the world, that the industry finds there is a lack of uniform calculation methods and comparable benchmarks. The uniform calculation methods are suggested developed by well-established, national organisations such as the Green Building Councils within their global network (De Wolf et al., 2017). Based on European statistics, recent scientific studies have indeed ventured to benchmark the environmental performance of European residential buildings, although applying different methodological settings (Gervasio & Dimova, 2018; Lavagna et al., 2018). The trans-national scope may face acceptance problems within the distinct local/national practices. For instance, the Danish methodological approach to LCA on buildings is founded on a collaborative effort involving the national building authorities, the Danish Green Building Council, research institutions as well as industrial companies and organisations (Birgisdóttir & Rasmussen, 2019). The Danish approach thus reflects the specific conditions within the current characteristics of the national sector (Rasmussen & Birgisdóttir, 2016).

DESIGN STRATEGIES FOR LOW-CARBON BUILDINGS

Several low-carbon design strategies are described and assessed in existing scientific literature. Design strategies that are directly related to the building site, e.g. soil stabilisation, are rarely included in the LCA practice although a potentially large share of the life cycle impact of a building may relate to these location-specific preconditions (Häkkinen, Kuittinen, Ruuska, & Jung, 2015). Rather, the primary focus in most LCAs is on the building as a generic design object. Single-focus evaluations of building designs, in which one strategy is assessed at a time, are present for a range of different low-carbon strategies, e.g. using bio-based materials (Salazar & Meil, 2009; Sodagar, Rai, Jones, Wihan, & Fieldson, 2011; Zea Escamilla et al., 2018), design for disassembly

(Tingley & Davison, 2012; Eberhardt, Birgisdóttir, & Birkved, 2018) and design with recycled/reused materials (Assefa & Ambler, 2017; Dara, Hachem-Vermette, & Assefa, 2019). A notable amount of research publications furthermore covers the operational aspect. i.e. reducing the life cycle impacts via design features that lower the impacts from energy use in the building (Mirabella et al., 2018). This type of research span the application of on-site energy generation based on renewable energy carriers (e.g. Goggins, Moran, Armstrong, & Hajdukiewicz, 2016; Houlihan Wiberg et al., 2014; Kristjansdóttir, Heeren, Andresen, & Brattebø, 2017) as well as reducing the energy demand in the building by use of additional insulation or technical equipment (Passer, Fischer, Sölkner, & Spaun, 2016; Sohn, Kalbar, Banta, & Birkved, 2017). However, the performances of single-focus cases cannot be compared on a harmonised level due to the differences in their methodological backgrounds as well as in the specific physical properties of the building (Malmqvist et al., 2018; Mirabella et al., 2018). Hence, on the background of the single-case studies it is not possible to conclude that one low-carbon strategy outperforms another strategy.

Some existing research also deals with multiple cases and multiple strategies in parallel. Allacker (2010), developed a method for investigating the pareto front of environmental costs against the financial cost of 16-88 different, conventional design options for floor construction, inner and outer walls, pitched and flat roofs as well as technical installations in different types of residential dwellings. Based on an analysis of these design variants in 16 different dwellings, she found that the average environmental optimization potential of a dwelling was 19% compared to current building practice. However, dwelling characteristics (e.g. layout, size and window area) presented an even larger optimisation potential of up to 57%. De Wolf (2017) investigated the embodied carbon of concrete, steel and timber-based structural solutions via more than 600 cases from practice and highlighted how there was a an order of magnitude in difference between the embodied carbon of the average and the best available structural design (De Wolf, 2017). Wiik et al. (2018) report from a larger-scale Norwegian research project in which several buildings were evaluated, each implementing specific strategies to achieving a ‘zero emission building’ (ZEB). Some general learnings about the building concepts are extracted from the research, although the authors highlight the uncertainties connected with the differences between building types as well as assessment practice (Wiik et al., 2018). Kristjansdóttir’s (2017) branch of the Norwegian ZEB research project put focus on the ZEB potentials of single-family houses. She concluded that a zero-balance of embodied and operational impacts is difficult to obtain, because the surplus energy, generated by on-site photovoltaics, substitutes a Norwegian electricity mix with a very low GHG intensity.

CATEGORISING DESIGN STRATEGIES

Malmqvist et al. (2018) presented a systematic categorisation of the low embodied carbon design strategies that are evaluated in literature. The categorisation mapped the different design strategies in terms of two key principles concerning material substitution and material efficiency, i.e. whether the strategy aims at lowering the embodied carbon by substituting conventional materials with low-carbon materials or whether the strategy aims at lowering the embodied carbon by reducing the amount of material used (while still providing the same function). De Wolf (2017) mapped low-carbon design strategies within the same two principles. Malmqvist et al. (2018) further mapped the strategies to indicate at which point in time the reduction potentials take place: i.e. potentials realised at the production stage of the building or potentials realised only if an assumed future scenario is fulfilled. Figure 2 shows a joint version of the strategies mapped in the work by Malmqvist et al. (2018) and De Wolf (2017).

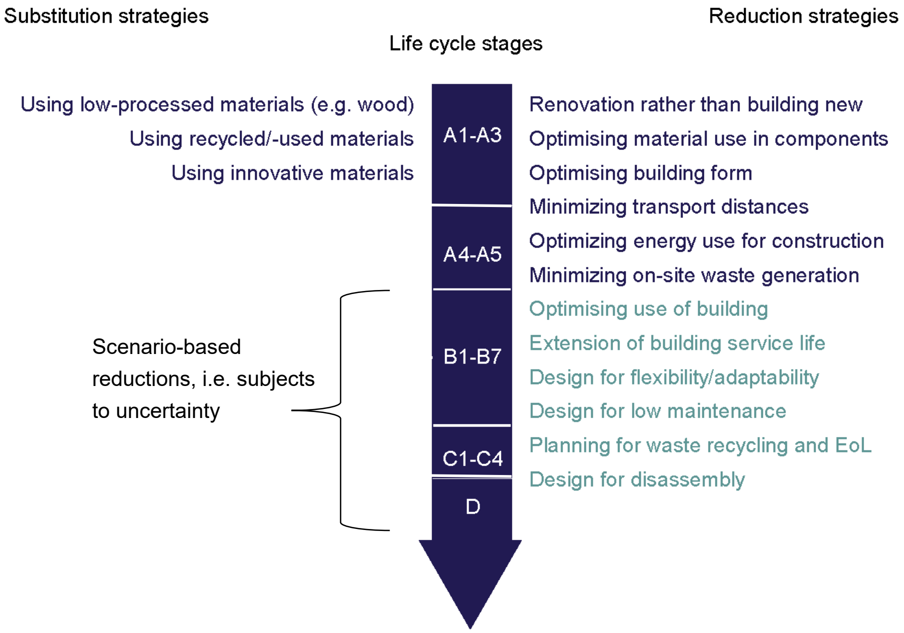

Figure 2. The design strategies for low embodied carbon mapped by Malmqvist et al. (2018) and De Wolf (2017) (adapted)

SUMMARY – STATE-OF-THE-ART

Decades of harmonisation efforts have resulted in a range of LCA standards applicable for the practical work of quantifying the environmental impacts of products and services. The ISO/TS 21931-1 and the EN 15978 are specifically tailored to whole buildings whereas ISO 21930 and EN 15804 are examples of key standards addressing the level of building products. In spite of the ongoing harmonisation work, large ranges in reported results of building LCAs are still observed. Existing literature explore the methodological variations either by reviewing parameters testified in other publications or by testing variations of selected parameter settings on case studies. However, a comprehensive and structured overview of methodological parameters is not found in existing literature.

It is recognised throughout building research and practice, that the variations in building layout as well as the methodological settings influence the results of the LCAs performed on buildings. This in turn means that there is no one-method-fits-all for the several countries investigating LCA benchmarks as part of regulation. Concerning the reduction targets for the Danish building sector, there is an obvious need for investigating the level of reference for building LCAs as well as clarifying how the specified assessment method is affected by the context of practice.

Existing literature provides various levels of categorising low-carbon design strategies. Keeping the methodological variations in mind, it is not possible to compare the viability of low-carbon strategies applied in single-case studies if these studies originate from different methodological backgrounds. However, there are several examples of assessed strategies, per single-case or samples, which may serve as inspirational literature for low-carbon building design. For the Danish uptake of low-carbon strategies, a harmonised comparison of low-carbon designs applied in practice is desirable.

CHAPTER 3. METHOD

This chapter elaborates on the choice of methods applied in the work of the current dissertation. The relationships between the applied methods and the individual publications are illustrated as an overview in Table 1 in the Reader's guide of Chapter 1.

HARMONISED LCA PROCEDURE

Life cycle assessment is used to quantify the life cycle carbon and embodied carbon of the cases presented in the current dissertation. In Publication IV, the LCA methods applied to the cases of the sample deviate because the cases originate from different authors. These differences in system boundaries etc. are mapped and analysed in Publication IV. The work carried out in publications I-III follow a harmonised LCA approach described in the following.

In parallel to the work undertaken within the current PhD project, the author of this dissertation has been involved in the continuous development of a unified, Danish LCA approach and tool for the national building sector. This work is documented in several publications (Birgisdóttir & Rasmussen, 2019; Kanafani, Zimmermann, Rasmussen, & Birgisdóttir, 2019; Rasmussen & Birgisdóttir, 2016). The LCAs conducted in publications I-III use this harmonised approach, summarised here in the reporting format of the EN 15978 standard. Details of the individual models can be found in publications I-III.

PURPOSE OF ASSESSMENT

The goal and intended use of the studies in publications I-III vary. In Publication I the goal is to compare four different design strategies for a low-carbon residential building. In Publication II, the goal of the LCA is to compare the carbon associated with an upcycled design versus a design for disassembly. The results are calculated with the allocation method implemented in the European standards EN 15978 and EN 15804. In Publication III, the assessment is carried out on a sample of residential building cases in order to derive a set of preliminary benchmarks for use in the Danish construction sector.

OBJECT OF ASSESSMENT

In all publications, results are evaluated based on a functional equivalent expressing the global warming potential per m^2 and per year of the building's service life. The building's service life equals the reference study period used for the analysis, in the Danish case for residential buildings this is assumed to be 120 years (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013). This choice of reference study period is uncommonly long, compared to most other studies of this kind using a 50-year horizon (Chastas et al., 2016; Chastas, Theodosiou, Kontoleon, & Bikas, 2018).

The system boundaries include the following life cycle stages and modules (see Table 2): product stage (A1-A3), replacements (B4), waste processing and disposal (C3-C4). Where relevant, for some of the analyses in publications I and III, the operational energy use (B6) is also included. In the remaining assessments, the operational energy use is left out of the assessment because the buildings all meet the 2015-level regulation on energy demand in buildings (The Danish Transport and Construction Agency, 2015). Hence, they all have a maximum energy use of 30+(1000/A[1]) kWh/m^2/y for heating, hot water provision, ventilation and cooling (e.g. 37 kWh/m^2/y for a 150 m^2 residential building). The choice of life cycle stages included in the Danish approach reflect the practical concerns related to availability of data and scenarios (Rasmussen & Birgisdóttir, 2016). This is further elaborated in Publication III. All buildings assessed with the harmonised method in publications I-III are residential buildings. In Publication I, the analysed houses are all single-family houses. The two cases analysed in publications II are a single-family house and a terraced house. In Publication III, the sample of cases are a mix of multi-family houses and terraced houses.

SCENARIOS FOR THE BUILDING LIFE CYCLE

The assessments in publications I-III follow the harmonised approach, although the individual design strategies assessed in publications I and II modify some scenarios concerning production (adjusting for recycled content in production), replacements (adjusting for a longer service life of the materials) and benefits in the next product system (crediting the displacement of virgin products). This is elaborated in publications I and II.

In the harmonised approach, all assessed buildings are subject to the same scenarios concerning replacement of materials, i.e. the production of a new material/component and the waste processing and disposal of the old

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[1] A being the conditioned area in m^2

material/component. The service lives of individual materials and components are specified via Aagaard et al. (2013). Scenarios for the end-of-life processes are determined from the Danish waste treatment practice reflecting business-as-usual (Rasmussen & Birgisdóttir, 2016).

QUANTIFICATION OF THE BUILDING AND LIFE CYCLE

The scope of the inventory includes foundation, structural frame and non-loadbearing elements. Finishing of all building elements are also included although connectors (nails, screws, brackets etc.) are not included. Neither is on-site waste. Only main aggregates of the technical systems are included in the inventories. In the cases of Publication I where operational energy use is included, the energy demand includes the regulated demand, i.e. heating, ventilation and hot water provision, as well as the additional user related demand, i.e. lighting and household appliances.

ENVIRONMENTAL DATA AND INDICATORS

In the harmonised approach, the German Ökobau is applied as the database providing the potential environmental impacts of materials and processes. Generic, average data are used throughout the analyses, supplied with EPD data in the rare cases where an average product did not exist in the database. Ökobau is tailored along the current European standards (EN 15978, ILCD) although some shortcomings also exists, e.g. concerning documentation of functional units (Gantner, Lenz, Horn, von Both, & Ebertshäuser, 2018). Ökobau generic datasets build on background data from GaBi (ibid.)

The environmental indicators in use also follow the applied database. I.e. data in Ökobau report the impacts concerning climate change at midpoint level as global warming potential in a 100-year time horizon (GWP_{100}), measured in kg CO_2 equivalents (CO_2e). The characterization factors applied are from the IPCC 2007 assessment report as specified for use by the EN 15804.

Environmental data for the energy use represent a projected approach modelling the politically set targets for decarbonisation of the grids. Hence, district heating and electricity impacts are modelled as being progressively based on more renewable energy carriers (Birgisdóttir & Rasmussen, 2019; COWI consulting, 2016).

SENSITIVITY OF RESULTS

The sensitivity of a model concerns the extent to which the variation of an input parameter, or a modelling choice, leads to variation of the results (Rosenbaum, Georgiadis, & Fantke, 2018). There are different approaches to the analysis of parameter variations, but they typically fall within the categories of local and global sensitivity analyses (Groen, Bokkers, Heijungs, & De Boer, 2017). Local analyses investigate parameter settings one at a time, and global analyses investigate how much each input parameter contributes to the output variance (ibid.). Uncertainty of modelling choices are dealt with in a different manner. Huibregts (1998) and Björklund (2002) characterise the different types of uncertainty and variability related to LCA, and suggest that the uncertainty related to choices be addressed with, for instance, scenario modelling, standardisation and peer review (ibid.).

Since the focus of this dissertation is on the context and the method of LCA in Danish practice, the influence of modelling choices on results are of special interest. Hence, no parameter variations (e.g. stochastically varying service life or input amounts of materials) have been investigated. Rather, the choices made for the harmonised method and the specific modelling is investigated in different ways in publications I-III. Publication I critically assesses the default and adapted scenarios relevant for the assessed building design strategies. This concerns the choice of allocation, the choice of reference service life of building materials, the scenario modelling of refurbishments and the scenario modelling of the future energy grid. Publication II investigates and discusses the modelling choices concerning allocation of impacts between neighbouring product systems. Publication III compares the modelling choices for the Danish benchmark derivation with the modelling choices of the North Italian benchmark derivation, specifically focusing on the scope of life cycle stages and the choice of database.

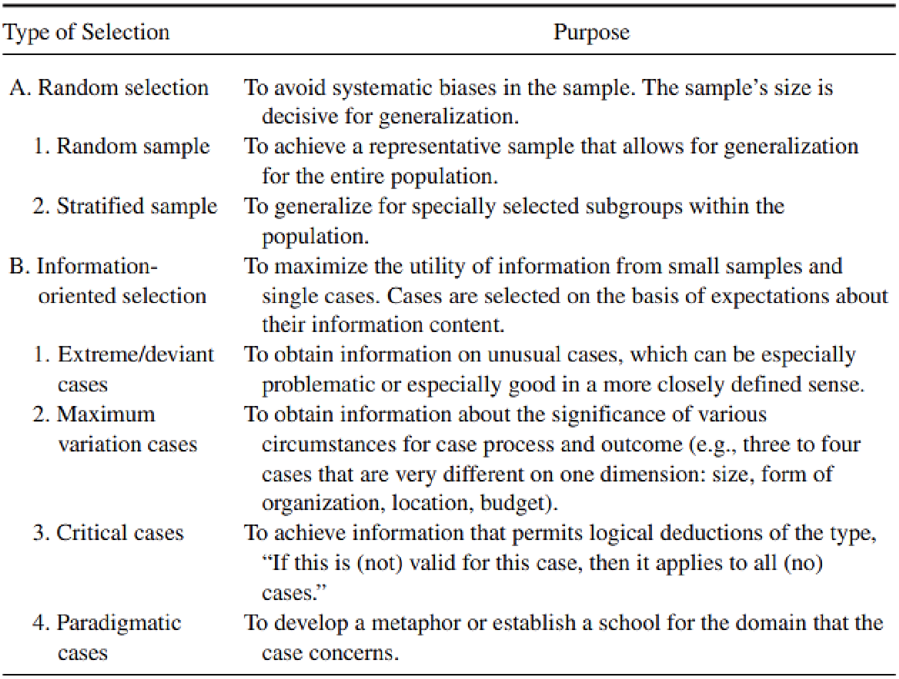
For the discussion part of this dissertation, emphasis is put on choices relevant to the further development of the harmonised LCA procedure used in the Danish practice. This includes qualitative evaluations of the functional unit, the benchmarking approach and the allocation in light of the net zero carbon future.

CASE STUDIES

The use of case studies plays an important role in current social science (Noor, 2008). However, case study research also frequently forms part of the research area of LCA on buildings (Ruuska, 2018), possibly due to the inherent uniqueness in quality and location represented by each individual building (Erlandsson & Borg, 2003). Yin (2003) defines a case study as an "…empirical inquiry that investigates a contemporary phenomenon within its real life context, especially when the boundaries between phenomenon and context are not clearly evident". Case studies, in individual or aggregated selections, are therefore used throughout this PhD work since the contextual focus is a core element along the technical focus on design strategies.

Publications III and IV make use of aggregated selections of case studies to quantitatively describe the ranges in results from the observed cases. Publication III further analyses the background methodology of the Italian and the Danish benchmark cases as a fingerprint of the contexts within which the applied methods are developed. Referring to the strategies for selection of samples and cases reproduced from Flyvbjerg (2006) in Table 4, the selection of the cases for publications III and IV can be characterised as random, although the samples are stratified, i.e. representing selected subgroups. In Publication II, two individual building cases are analysed and compared. The two cases represent two ‘extreme cases’, i.e. deviating designs of the circular economy paradigm, and they are selected “…on the basis of expectations about their information content” (see Table 4). In Publication I, the six building cases analysed represent the ‘maximum variation’ cases (ibid.), denoting the fact that the cases are set within a range of similar defining parameters (e.g. size, cost, developer, location) albeit differing in the chosen design for carbon reductions. More details on the case samples and cases can be found in the individual publications I-IV.

Table 4. Strategies for the selection of samples and cases (Flyvbjerg, 2006).



Type of Selection	Purpose
A. Random selection	To avoid systematic biases in the sample. The sample’s size is decisive for generalization.
1. Random sample	To achieve a representative sample that allows for generalization for the entire population.
2. Stratified sample	To generalize for specially selected subgroups within the population.
B. Information-oriented selection	To maximize the utility of information from small samples and single cases. Cases are selected on the basis of expectations about their information content.
1. Extreme/deviant cases	To obtain information on unusual cases, which can be especially problematic or especially good in a more closely defined sense.
2. Maximum variation cases	To obtain information about the significance of various circumstances for case process and outcome (e.g., three to four cases that are very different on one dimension: size, form of organization, location, budget).
3. Critical cases	To achieve information that permits logical deductions of the type, “If this is (not) valid for this case, then it applies to all (no) cases.”
4. Paradigmatic cases	To develop a metaphor or establish a school for the domain that the case concerns.

REVIEW

Reviewing as a research method is used throughout the work of this dissertation in order to frame the work within existing research. For Publication IV, however, the reviewing forms the entire basis of the results and analysis presented. Publication IV builds on a split review in which 1) a sample of case studies are reviewed in a meta-analysis in terms of results and methodological approach, and 2) a review of scientific literature is used as a foundation for the research synthesis of methodological approaches presented in these case studies.

Research syntheses and meta-analyses are commonly aimed at producing "…new knowledge by making explicit connections and tensions between individual study reports that were not visible before" (Suri, 2011). Cooper and Hedges (2009) identify five stages in the review process: problem formulation, literature search, data evaluation, data analysis, interpretation, and presentation. The literature search for Publication IV was conducted, as described above, with two parallel foci. Hence for 1), the meta-analysis of results and methodological approach, a collection of 61 building case studies was used. These cases represented current as well as best-practice buildings from 10 different countries. All cases informed about the embodied energy and carbon of the building and reported these figures in a standardised template developed within the IEA EBC Annex 57 project (Birgisdóttir et al., 2017). In the data analysis of the studies, the individual results were mapped, and ranges of embodied impacts for the different life cycle stages were derived for new buildings as well as refurbishments (see also Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, & Birgisdóttir, 2019).

In Publication IV's pathway 2), the research synthesis of methodological approaches, a literature survey with key phrases on the topic was conducted in Scopus and Web of Science. The literature search was supplemented by a snowball-approach to capture additional literature of relevance. Methodological issues that were relevant to embodied impacts were identified in the sample of literature and was mapped in the step-by-step application framework of the EN 15978 standard of LCA of buildings. Using this framework for the research synthesis ensured that the identified methodological issues were mapped in relation to the actual process for conducting a building LCA. In this sense, the application framework offered a structured and comprehensive background for identifying the methodological issues that were already addressed in existing literature as well as the additional methodological discrepancies that were observed from the compilation of the Annex 57 case studies.

CHAPTER 4. FINDINGS

The findings presented in this chapter are structured into the two areas of focus outlined in Chapter I, i.e. the assessment practice and the design strategies employed under Danish conditions. Publication I, II and III contain benchmarks and analyses of selected low-carbon design strategies for building design. Publications II, III and IV contain analytical aspects concerning LCA in method and practice. The implications of the individual publications are summed up in the final section of this chapter.

ASSESSMENT OF BUILDINGS AND STRATEGIES

FOUR STRATEGIES FROM BUILDING PRACTICE

Publication I assesses five buildings applying a total of four different design strategies concerning up-/recycling (Upcycle House), long service life of materials (Maintenance-Free House I and II) – the Traditional and the Innovative), design for adaptability (Adaptable House), and low energy use (Quota House). Each of the cases are assessed with the harmonised LCA method and individually compared with a reference house, representing an average Danish single-family house. The five buildings were constructed in Nyborg, Denmark as part of a project funded by a philanthropic organisation, the Realdania By & Byg. All building cases were confined within the same budget, location and energy performance. The buildings were assessed with the harmonised Danish method, although specific scenarios were defined for each strategy: For the Upcycle House, specific upcycle factors were determined to modify the generically based environmental data. For the Maintenance Free Houses I and II, specific scenarios for prolonged service lives were defined. For the Adaptable House, specific scenarios concerning the adaptive actions were defined. Finally, for the Quota House, specific reductions in the energy demand were assumed because of the building design. See Publication I for further details.

Figure 3 shows the carbon profiles associated with the different life stages of the buildings. The assessment shows that the up-/recycling and the prolongation of service life of materials prove to be the most effective strategies for low-carbon housing. These design strategies cause 2.9-3.7 kg CO_2e/m^2/year, which corresponds to a saving of up to 40% compared with the 5 kg CO_2e/m^2/years caused by a reference house over the full life cycle. However, the saving potentials of the Maintenance Free Houses are very dependent on the scenarios for replacements. The same scenario dependency concerns the Adaptable House that causes practically the same level of embodied impacts as the Reference House, but a 43% reduced impact from the defined refurbishment actions. The Quota House, applying a design that nudges energy savings, also shows potential emission savings of up to 20% compared to the emissions from building operation and appliances in the Reference House. However, the modelling/assumptions concerning the expected future decarbonisation of the energy grids decisively influence these potentials.

Note that Figure 3 presents the Upcycle House as having a negative impact from production stage. As explained in Publication I, this negative impact is not caused by the use of recycled materials. This type of emission profile is only possible due to the use of wood-based materials. This is further elaborated in the discussion.

DESIGN FOR DISASSEMBLY – A MULTI-SYSTEM ORIENTED DESIGN STRATEGY

In Publication II, the life cycle embodied GWP is calculated for an up-/recycled based building and a Design for Disassembly (DfD) building. The up-/recycled building is also used as a case in Publication I. In Publication I, the background data concerning the ‘upcycle factors‘ (see Table 2 in Publication II and Table 2 in Publication I) was refined and thereby serve as the more updated model. The results of the up-/recycled building is therefore reported in the previous section.

The DfD building is a terraced house in two storeys made with concrete elements, mineral wool insulation, façade tiles and a flat roof. The building designers chose a range of materials and elements that were directly reusable (with only limited cleaning/transport processes) in a second product system. This concerns beams, slabs, wall elements, façade system of clays tiles, wood wool ceiling boards, gypsum wallboards, and carpet tiles. The life cycle GWP was calculated with the harmonised Danish method. The life cycle GWP of the specific building’s life cycle is not directly credited for the future reuse, which is only reported as additional information in Module D (see Table 2). In spite of the design effort made to reduce the carbon footprint, the DfD building yields a life cycle GWP of 6.7 kg CO_2e/m^2/year, which is higher than the span (2.9 - 6.0 CO_2e/m^2/year) from the buildings in Publication I and 12% higher than the reference benchmark of 6.0 CO_2e/m^2/year found in Publication III.

However, in an enlarged system perspective, the case of the DfD building exemplifies some important issues. The building delivers reusable materials and elements of high quality to other systems. Some of these materials and elements will be available when the building is dismantled and others will be

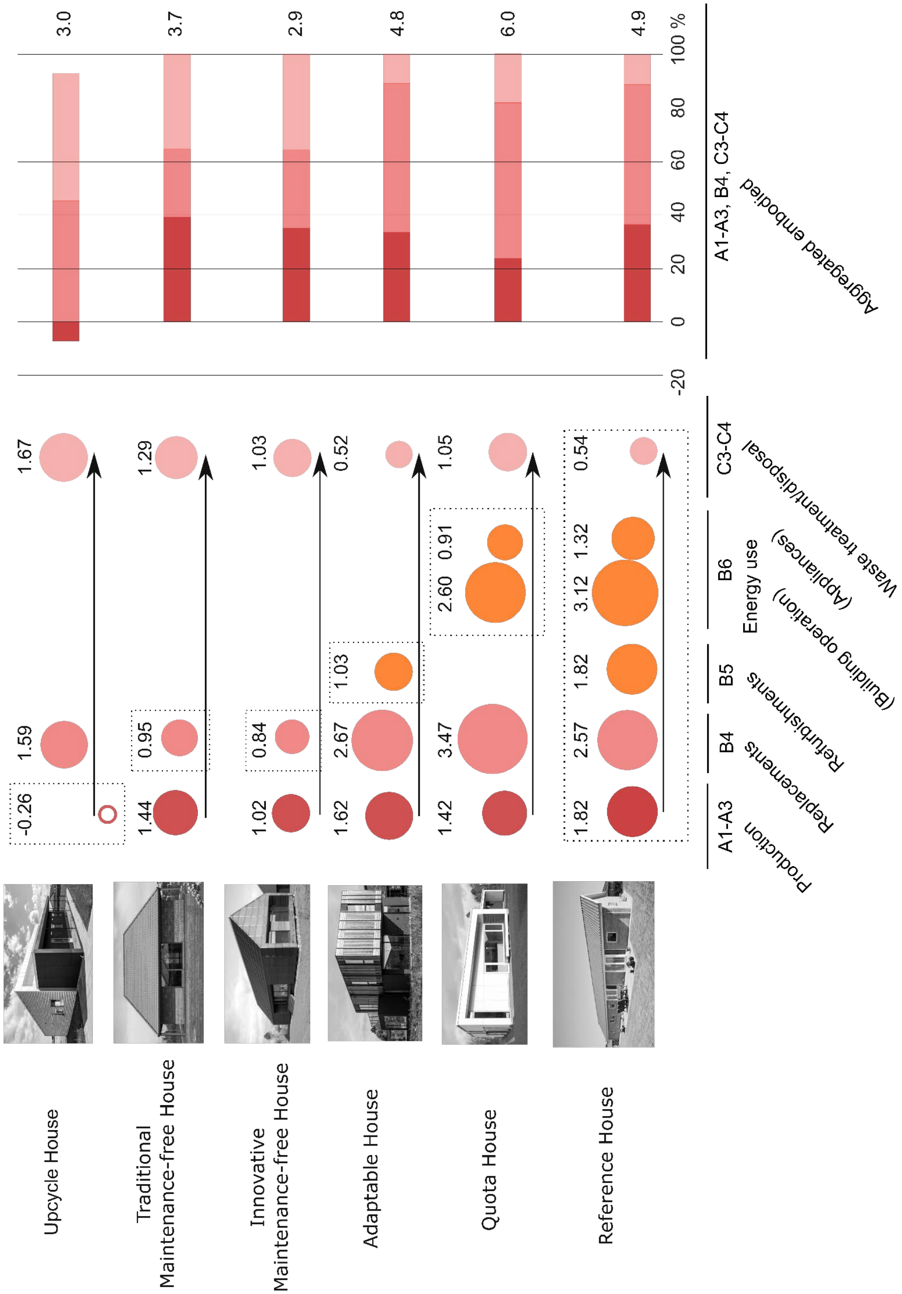


Figure 3. Carbon profiles of the MiniCO$_2$ houses. Orange colours denote the life cycle stages not included in the aggregated embodied emissions of the buildings. From Publication I (Rasmussen, Birkved, & Birgisdóttir, 2020)

available sooner. Figure 4 shows the GWP associated with the specific available materials. The large volume of concrete elements only accounts for 25% of the total GWP credits in future systems, whereas the aluminium profiles (800 kg in total) account for 34% of the potential credits. However, both of these potentials are only available at the end of the building's service life, i.e. the potential is associated with a notable uncertainty. The potentials of specific materials and the considerations about the timing of availability highlight the fact that DfD solutions could focus on facilitating the reuse/recycling of the shorter-lived elements of high benefit potentials. In this way, focus is redirected at the benefits that are available sooner. Further, this short-/medium term perspective would reduce the uncertainty concerning the far-future reuse by focusing on the more current emissions and potentials.

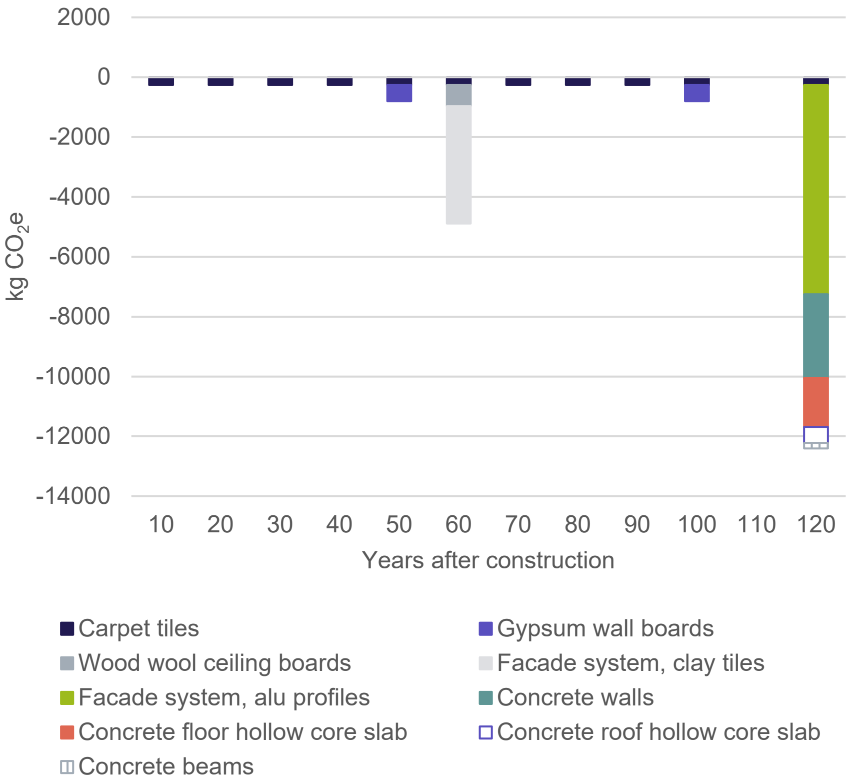


Figure 4. The potential GWP benefits in next product system (module D) associated with the specific available materials of the DfD building. From Publication II (Rasmussen et al., 2019)

LCA BENCHMARKS - IDENTIFYING A LEVEL OF REFERENCE

Publication III presents reference LCA benchmark values for residential buildings in a Danish and North Italian context. The calculated embodied GWP benchmark of the Italian context is 3.8 kg CO_2e/m^2/year, whereas the Danish is 6.0 kg CO_2e/m^2/year, hence the Italian is 37% lower than the Danish. This difference exists even though the two contexts align in several places concerning the method applied to calculations of the embodied impacts. First, a long RSP of 120 and 100 years is used for Denmark and Northern Italy respectively. Second, the selection of life cycle stages included in the method is similar, except for the Italian context applying also the transport-to-site and the construction process. However, these two stages collectively contribute with less than four percent of the total result for the embodied Italian GWP. Conversely, the Danish inventory scope include technical installations and foundations that are not included in the North Italian approach. In the Danish embodied benchmarks, these elements constitute 13% of the GWP. The difference between the benchmark values can thus be associated to a limited extent with the differences in life cycle stages and inventory scope. However, the previously mentioned differences in choice of database, the scenario definitions of specific materials as well as the service lives of the materials remain as explanatory parameters to the difference observed between the North Italian and the Danish reference benchmarks.

In the Danish case, the contribution of the roof element to the GWP results is notable. Approximately 30% of the impacts stem from the roof in the Danish case (see Figure 5). In the North Italian case, only 5% is associated with the roof construction (see Figure 2 in Publication III, Appendix C). This difference reflects how the Danish cases primarily consist of buildings with bitumen roofing sheets. These are assumed frequently replaced (every 20 years), which entails an emission-intensive incineration process. The fact that bitumen sheets are so significant to the results cause for some warnings: The small sample used in the Danish benchmark derivation (only seven cases were available) needs further enlargement to avoid biases, i.e. to ensure that the roof types are representative to the building stock in focus. Further, the harmonised Danish LCA approach should critically assess and adapt the data in terms of EoL scenario and service life. For instance, a double-layered bitumen roofing may entail a longer service life for the roof covering. Nonetheless, the standardised modelling prescribes the application of a 20-year service life regardless of the number of layers.

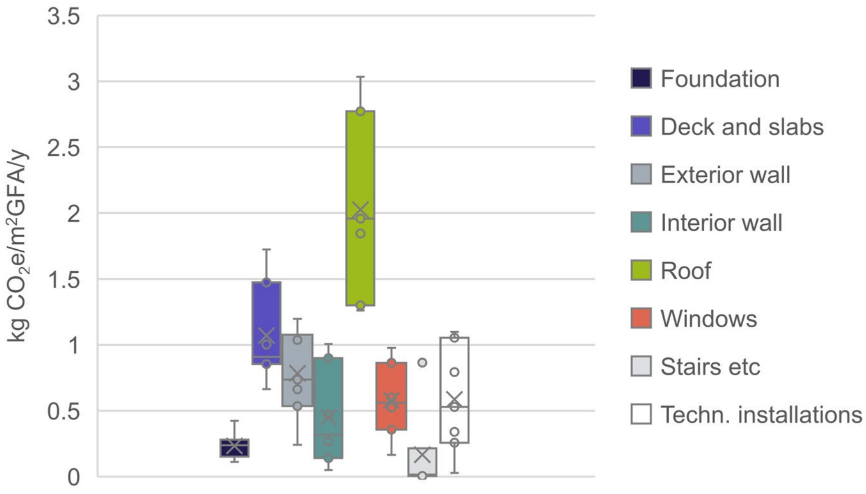


Figure 5. Variability for the life cycle embodied GWP from different building elements in the Danish building cases. Adapted from Publication III (Rasmussen et al., 2019)

ANALYSIS OF LCA METHOD AND PRACTICE

ALLOCATION OF IMPACTS BETWEEN DIFFERENT LIFE CYCLES

The allocation of environmental impacts between different systems and processes is a well-known issue of debate within the LCA society (Allacker et al., 2014; European Commission - JRC, 2010). Allocation is applied in LCA wherever two interlinked systems are assessed separately, i.e. in relation to the material and emission flows at the border between a defined system and the external processes. At material level, the allocation is usually integrated in the data expressing the environmental impacts, i.e. the allocation is an inherent feature of the database used for an assessment. At the more aggregated building level, however, the allocation is carried out by the individual assessor. Publication II explores the allocation between systems in the cases of two low-carbon design strategies frequently applied in the context of circular economy; 1) up-/recycled materials as the input to the building system under study and 2) recycled materials as the output of the building system under study, such as the case of ‘design for disassembly’ (DfD). In the European harmonized approach to building LCA, expressed via the EN 15978 standard, the so-called 100:0 or the cut-off approach is used for allocating environmental impacts and benefits between systems.

Figure 6 visualises the logic behind the 100:0 approach for different interlinked building systems. System 0 exports recycled materials that enter System 1 practically burden-free (save for the preparatory processes). The input of recycled materials is thus a benefit for System 1. System 0 accounts for all emissions related to the production of virgin materials, regardless of the potential to substitute virgin materials in the subsequent System 1. In this sense, the 100:0 allocation approach of the standard results in lower level GWP from the up-/recycling strategy, especially from the production stage, whereas the DfD strategy does not realize an environmental advantage in its first life cycle. The European standards thus represent an end-of-pipe focus on lowering current emissions rather than crediting current systems for (potential) future emission savings. The strategies assessed in Publication II thereby highlight one of the crucial differences between the product perspective outlined in the European standards and the larger system perspective of the circular economy.

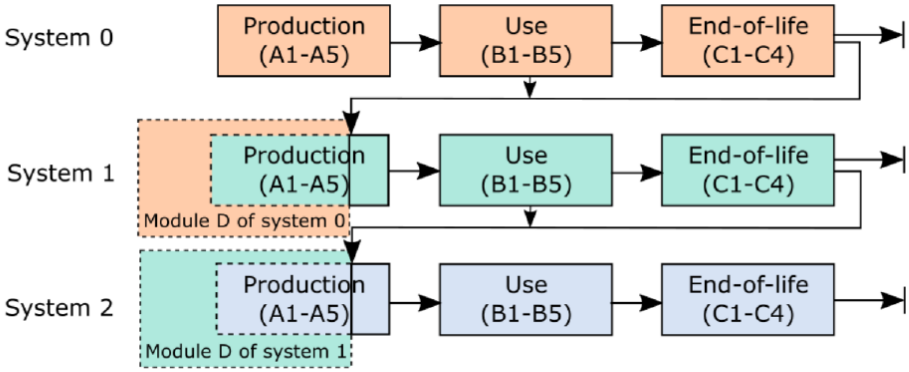


Figure 6. Principle of impact and benefit distribution in the 100:0 allocation approach of the EN 15804/15978 standards. From Publication II (Rasmussen, Birkved, & Birgisdóttir, 2019)

LCA BENCHMARKS - ASSESSMENT PRACTICE

Publication III focuses on assessment practice in two specific contexts. The publication uses two recent benchmark derivation processes from Denmark and Northern Italy to evaluate the differences observed in results and in the background methodology. A number of the methodological issues highlighted in Publication IV becomes apparent in the comparison of the two benchmark processes, for instance concerning the background data used for the comparison. A comparison between selected construction materials of the two databases Ökobau and Ecoinvent (used in the Danish and the North Italian system respectively) reveals issues related to data as well as modelling choices. In Figure 7, the GWP profile associated with construction wood stands out. Ökobau data include the stored, biogenic CO_2 of wood products whereas the Ecoinvent-based results do not. This discrepancy exists even though the characterisation method is the same in both cases (albeit different version, see Table 3 in Appendix C). The inclusion of stored CO_2 will lead to a different profile for the modelling of the Danish buildings because the CO_2 uptake (the negative GWP) is associated with the production stage and the release of the CO_2 is associated with the end of life stage. In this sense, the modelled GWP profile of a Danish building containing construction wood will have more fluctuation over the life cycle than the North Italian.

Figure 7 also shows how the different scenario settings affect the profile of individual building materials profoundly. In the Danish case, the EoL scenario for bitumen sheets corresponds to the current practice of incineration, whereas the North Italian case assumes a landfill of the material. This results in a five-fold difference between the GWP profiles of the single material. Lastly, Figure 7 shows the inherent difference between datasets from different databases, especially the datasets concerning mineral wool. A 20% difference between the GWP profiles of the two databases can be noted. For this type of difference, no apparent explanations are visible other than the general difference between databases, e.g. different system boundaries, different production technologies etc. (see e.g. Martínez-Rocamora et al., 2016; Takano et al., 2014).

The choice of database is but one choice in a collection of choices made for a benchmark system. Whereas data for Publication IV does not contain this level of detail, Publication III delves into the reasons behind the methodological choices of the two benchmark methods. The context-related choices mirror how the technical, well-defined assessment systems of the EN 15978, in practice, are set within a socio-technical reality. In this reality, the comprehensiveness of an assessment may be compromised by other concerns and needs of the actors developing and using the system in practice. Through an in-depth analysis of the two benchmark contexts, Publication III presents five distinct areas of compromises/trade-offs in play in the definition of a benchmark system. The first of these trade-offs concerns the fundamental purpose of the system. For instance, does the benchmark system aim to position buildings relative to ‘the average building’, thereby promoting slight improvements relative to the average performance? Or does the benchmark system aim to disclose how near (or far) the assessed buildings are to the target of zero emission buildings? Although there are examples of a combination of the two perspectives (Hollberg, Lützkendorf, & Habert, 2019), the Danish and Italian cases in Publication III both aim for a step-wise improvement of the building stock based on the current average.

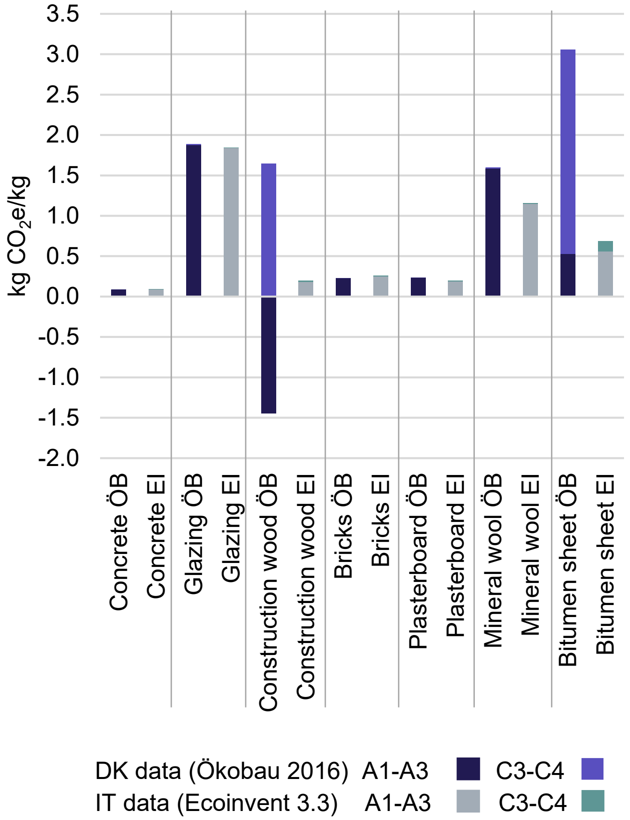


Figure 7.Impacts from selected construction materials from the Ökobau 2016 database and the Ecoinvent 3.3. database. From Publication III (Rasmussen et al., 2019)

The second of the trade-offs is a temporal concern about the choice of reference study period (RSP) and the functional unit used for presenting and comparing results. The functional unit is frequently expressed in impacts per m^2 per year of the RSP, which is also the case in the Danish system. In this sense, a long RSP captures the advantages of durable materials and components by distributing their impacts over the course of 120 years. However, this technical approach neglects the risks and uncertainties associated with such an extensive temporal perspective. The building may not last the 120 years due to a multitude of other reasons other than the technical durability (see e.g. O'Connor, 2004; Østergaard et al., 2018). Further, distributing impacts over 120 years inevitably passes on a GWP load to future inhabitants of the building. Despite the fact that a notable part of the emissions takes place in the years around the actual construction (see Publication III).

The third trade-off concerns the issue of representativity versus availability. This trade-off is largely associated with the choices of different types of data for the assessment system. For instance, although environmental data related to Danish products would be the most representative solution, the German database Ökobau met the practical criteria of availability. Another level of concern about data relates to the sample of buildings used to derive the benchmarks. Although a broad sample representing multiple types of residential buildings would be the preferred sample, a limited sample was available at the time of the benchmark derivation.

The fourth trade-off revolves around the ease-of-application to the users of the system. Although a comprehensive benchmark system, for instance including all life cycle stages, would yield the most accurate results, this is compromised against the assumed workload in practice.

The fifth trade-off concerns method consistency versus method integration. This is relevant for instance in the Danish compromise of incorporating existing regulation on energy performance into the benchmark system, instead of running an LCA-based system in parallel.

The trade-offs identified in Publication III vividly put the imperfect solutions of application practice on display. The analysis thus highlights why assessment systems and derived benchmarks vary, depending on their context. The analysis further emphasises the need for frequent reconfigurations of the systems to strengthen compliance with scientific recommendations, and, in a longer term, compliance with the ambitious targets on GHG reductions.

METHOD-BASED DIFFERENCES IN EXISTING CASES

Publication IV addresses the research gap presented in Chapter 2 about the lack of a comprehensive and structured overview of methodological parameters influencing the results of building LCAs. Publication IV contains a meta-analysis of existing case studies reported within the IEA EBC Annex 57 project. Sixty-one building cases from 10 countries provided the background information for the mapping of results and methodology. The meta-analysis shows profound variations in the reported levels of GWP from the cases. As shown in Figure 8, the production stage (A1-A3) of the building life cycle varies between -7 and 1100 kg CO_2e/m^2. When mapped in terms of building type (see Figure 9), notable overlaps can be found between the types, indicating that the specific type is less relevant to the variations found. However, when the cases are mapped in terms of their background database (see Figure 10), it becomes obvious that some databases, e.g. the Japanese IO database and the ICE database, seem more affiliated with higher levels of CO_2e. Each of these parameters, i.e. the building type and the database, are only indicators of the multitude of differences behind the cases. Within each building type, there will be large differences between the layout of the buildings, the inventories etc. Within each database, there may be differences in GWP definitions, representativity of data etc.

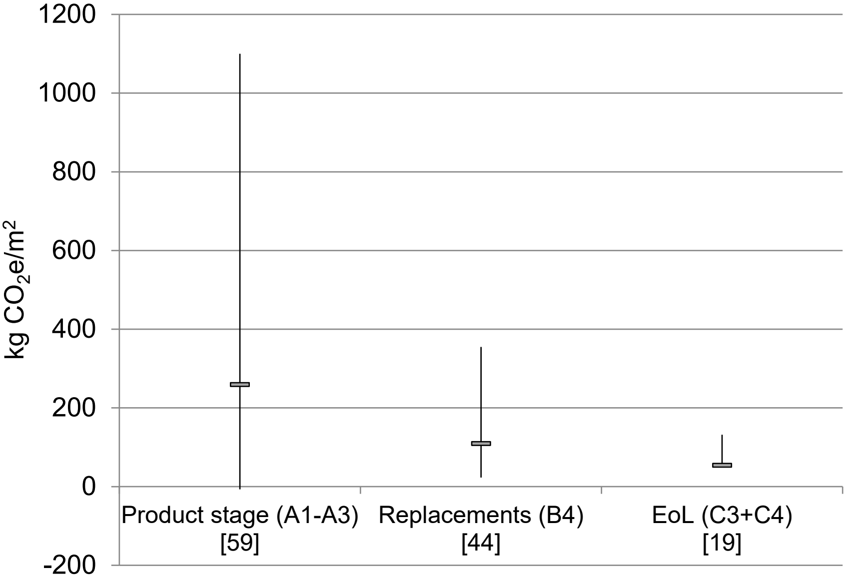


Figure 8. Averages and ranges from selected reported life cycle stages of the Annex 57 case studies. Square brackets indicate number of case studies included in the displayed ranges. From Publication IV (Rasmussen et al., 2018)

Based on the results of the meta-analysis it is not possible to pinpoint the most effective strategies towards a building design entailing a low level of embodied carbon. The variations between methodological setups of the cases are simply too large. This in turn means that an utmost degree of transparency is needed to supplement the further communication and interpretation of a given case study. Earlier research has approached this documentation need in a rather schematic approach, i.e. highlighting specific, or selections of, methodological issues that affect the results of a building LCA. Publication IV further presents a systematic overview of the methodological issues that collectively explains the large variations found between existing case studies in academia and grey literature.

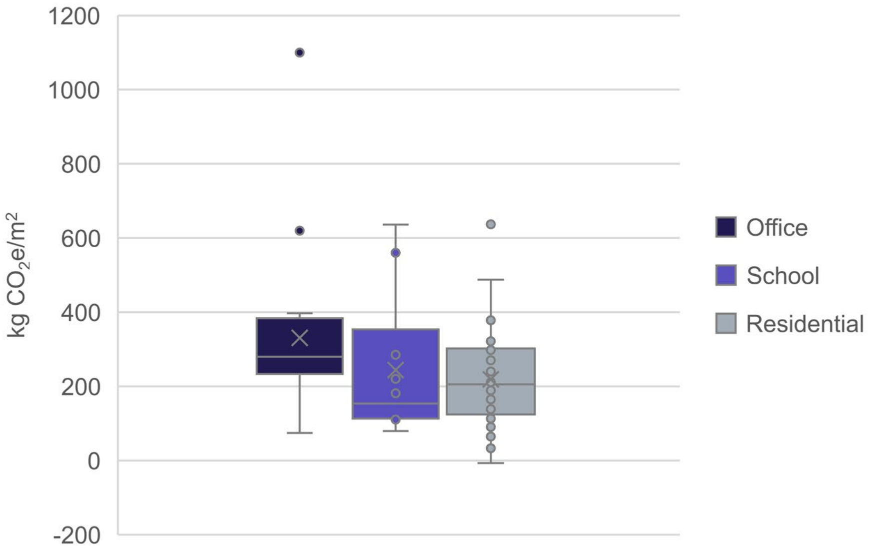


Figure 9. Boxplot illustrating the distribution of embodied carbon from Annex 57 cases, based on reported characteristics for building use type. From Publication IV (Rasmussen et al., 2018)

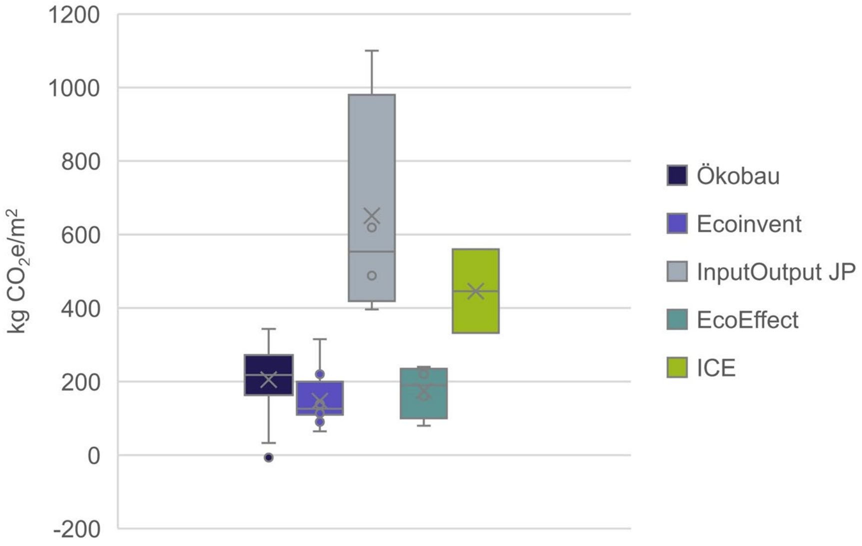


Figure 10. Boxplot illustrating the distribution of embodied carbon from Annex 57 cases, based on reported characteristics for the applied database. From Publication IV (Rasmussen et al., 2018)

The systematic overview of methodological issues from Publication IV is reproduced in Table 5. The overview is structured along the flowchart of the assessment process given in EN 15978, ensuring that all methodological choices addressed in the course of an assessment are evaluated. Publication IV does not evaluate to which extent each of these methodological choices affect the results of a building LCA. Further research could revolve around this extensive analysis. However, the combination potentials between the methodological choices, together, cause a multitude of ways in which the results of an LCA are affected.

Table 5. Points of attention concerning methodological choices and transparency in calculations of embodied carbon. Adapted from Publication IV (Rasmussen et al., 2018)

Process steps according to EN 15978	**Information required, based on EN 15978**	**Points of attention identified in literature and case practice**
Identification of the purpose of assessment	Goal Intended use	Goal and intended use of study affects subsequent methodological choices, e.g. about functional equivalent, system boundaries etc.
Specification of the object of assessment	Functional equivalent	Lack of international definitions and terminology to describe functional and technical requirements (e.g. zero-emission-building) as well as referencing units (definitions of m^2)
	Reference study period	Reference study period set: - arbitrarily (as a numerical exercise to report annualised results) - as the required service life of building (although no consensus exists on how to determine this)
	System boundaries	Variations in system boundaries at different levels: - selection of included building life cycle stages - selection of building model scope
	Description of the physical characteristics of the building	Uniqueness of building design and construction practice

Scenarios for the building life cycle	Description of scenarios for all periodic operations	Variations in available information on service life of materials and products
	Description of scenarios for all included life cycle stages	Variations according to national practice, guideline and/or regulation, for instance: - waste management - building site regulations
Quantification of the building and its life cycle	Quantification of all net and gross amounts of materials and products in the building's life cycle	Potential simplifications of the building scale LCI
	Type of LCI data	Variations in sources and their level of detail (drawings, BIM data etc.)
Selection of environmental data and other information	Environmental data used for calculations	Representativity of data Generic or product specific data System boundaries of database(s): - including/excluding carbon storage in biomaterials - width of included input and output substances and resources in data's modelling background
Calculation of the environmental indicators	Choice of indicators and characterisation factors	GWP definition: - included GHG emissions - characterisation factors used for GHG other than CO_2 - temporal scope of GHG emissions
	Calculation method for total life cycle impacts	Input-output, hybrid or process based modelling approach of data

Based on the findings from Publication IV, building LCA practitioners are recommended to address the points of attention in Table 5 to ensure the transparency needed for third parties to subsequently understand and use the studies. Design practitioners, seeking inspiration for low-carbon building design, are recommended to evaluate existing, inspirational studies in light of the points of attention in Table 5 to become familiar with the methodological choices that may cause a change in results in a different methodological setting. In the further development of harmonised methods, the points-of-attention should be kept in mind to ensure that rules in practice, for a specific context, does not allow for widely different methodological settings and background choices.

SUMMARY – FINDINGS FROM PUBLICATIONS

Publication I, II and III contain analyses of low-carbon design strategies from Danish building practice.

Publication I assesses four different design strategies applied in five different buildings erected in Denmark. The comparison with a reference single-family building shows that recycling proves to be an effective design strategy for low-carbon housing with a saving potential for embodied carbon around 40%. Planning for long service life and adaptability are strategies that may have their merits but are very dependent on the set scenarios. Further, there may be life cycle benefits in a strategy of designing for low energy consumption. However, the scenario modelling of the ongoing decarbonisation of the energy system influences these potential benefits.

Publication II analyses a residential building containing DfD elements, i.e. elements designed for direct reuse in a second life cycle. The assessment finds that this design strategy yields a profile for embodied carbon 12% higher than the reference values found in Publication III. This is based on the current assessment practice containing a product focus. The analysis also finds that notable saving potentials pertain to the second use of the materials. Hence, in an enlarged systems perspective, the DfD solutions may be viable. However, to reduce uncertainties associated with the long time perspectives, DfD solutions could preferably focus on facilitating the looping of shorter-lived elements of high potentials. This will generate savings in a second product system.

Publication III derives LCA benchmark values of a sample of residential buildings and finds that the reference embodied GWP value is 6.0 kg CO_2e/m^2/year over a 120-year reference study period. The study also finds that a notable share of the embodied impacts originated from the replacement and incineration of materials for the roof elements. Further work is needed to ensure representativity of the sample of buildings, but the study presents a preliminary set of LCA values that can be used as guiding values for benchmarking the low-carbon design initiatives, and for further developing limit and target values.

Publications II, III and IV contain analyses of LCA in method and assessment practice.

Publication II analyses two case buildings representing two distinct low-carbon strategies often considered as part of the circular economy: the up-/recycling of products and the design for disassembly. The analysis finds that the product focus outlined by the EN 15804/15978 standards discourage the enlarged system perspective required to assess the circular properties of a design for disassembly.

Publication III investigates how the method applied for the benchmark derivation represents a series of methodological choices that are not purely science-based, but also influenced by the context in which the method is established. This represents a number of fundamental trade-offs for the modelling. Based on the in-depth analysis of a Danish and a North Italian benchmark derivation, horizontal comparisons between benchmarks from different contexts are discouraged. The differences observed in material GWP values and scenario definition furthermore call for a rigid approach to strictly defining the rules-in-practice concerning database and scenario settings in benchmark systems.

Publication IV concludes that the large ranges in reported embodied GWP results of buildings impede the identification of effective low-carbon strategies on a general level. The publication calls for assessment transparency and presents a systematic overview of the points of attention that need considerations for understanding the methodological differences between studies.

CHAPTER 5. DISCUSSION

This chapter puts the findings into perspective by elaborating on three themes that are relevant to the current Danish approach to building LCA. The summary of this chapter further synthesises the themes from the findings and discussion to provide an overview of the dynamics within the Danish context of building- and assessment practice.

THE TEMPORAL PERSPECTIVE OF EMISSIONS

The work of the current dissertation emphasises the embodied emissions from the life cycle of new buildings. However, the technical life cycle of a new residential building is extensive, in the Danish context assumed 120 years. Considering the fact that global emissions need to be drastically controlled and reduced within a few decades, this long time perspective applied on the building models is debatable. Figure 11a maps the embodied emission profiles (from production, replacements and EoL) of the seven different buildings assessed in publications I and II. Figure 11a points to the Upcycle House as having the lowest outset of emissions from the production stage. This is not only caused by the use of recycled materials but also by the use of CO_2-storing biomaterials, mainly construction wood. The CO_2 storage (e.g. -800 kg CO_2e/m^3) is modelled at the production stage (in A1, see Table 2) and the release of same CO_2 is accounted at the EoL (in C3 or C4, see Table 2). This modelling of the temporarily stored biogenic CO_2 is common practice under the EN 15804 standard and subsequent product category rules such as EN 16485 about wood and wood-based products for use in construction. However, accounting for the timing of the storing and release of biogenic CO_2 in LCA is an intensively debated topic, and the various approaches can lead to differences in the final results (Brandão et al., 2013; Tellnes et al., 2017).

If indeed the targets of carbon neutrality by 2050 are reached, in full or partially, the emission profiles of the assessed buildings will look remarkably different from initially modelled by use of the Danish harmonised method. Modelled emissions from 2050 and onwards will then not take place, or will be compensated one-to-one by CO_2-storing activities and technologies. This post-2050 carbon neutrality is represented in the emission profiles of Figure 11b by the dotted lines connected with each building's profile. In this sense, modelling the full life cycle of a building based on today's preconditions is flawed from the outset. Thus, a zero-carbon future redirects attention from the full life cycle to the initial emissions taking place at the time of the construction (Röck et al., 2020; Säynäjoki, Heinonen, Junnila, & Horvath, 2017). Future development of LCA methods in practice should integrate this perspective.

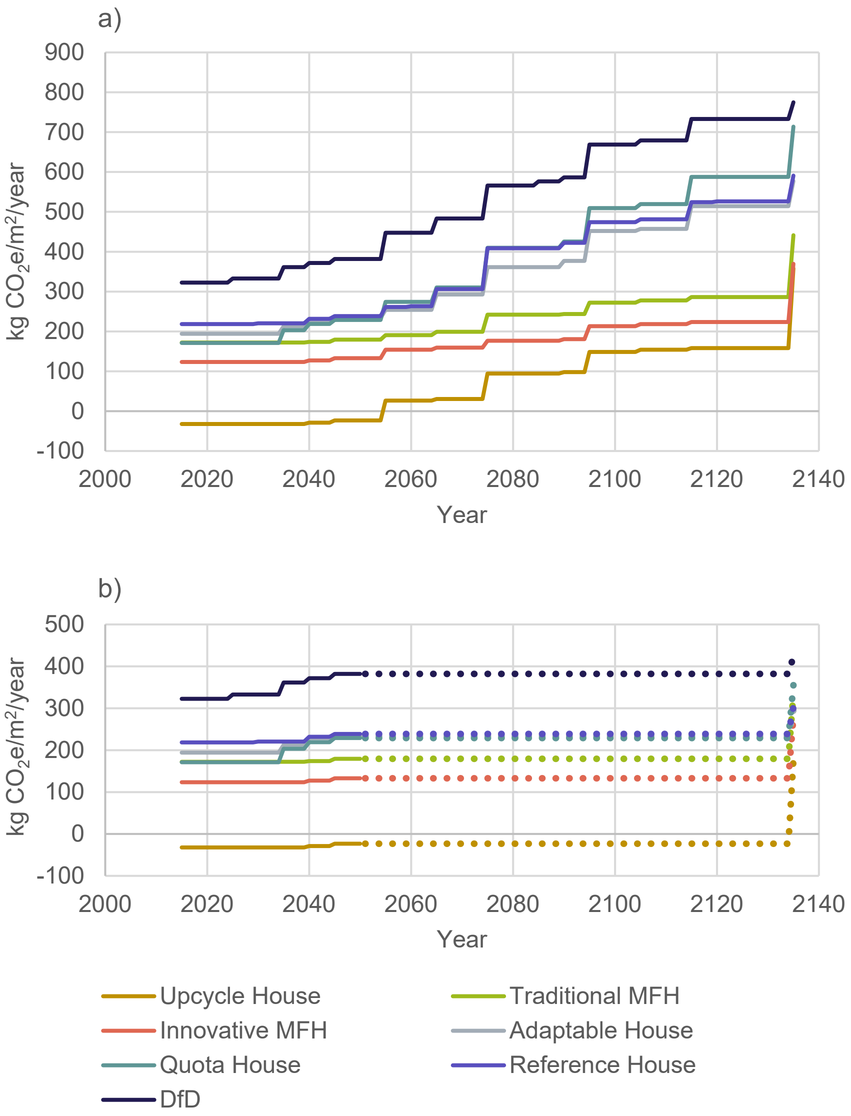


Figure 11. Accumulated carbon emissions from the production, replacement and end-of-life stages of the MiniCO₂ Houses, the Reference House and the DfD house as calculated with the harmonized method (a) and with a net zero future from 2050 (b). Adapted from Publication I (Rasmussen et al., 2020)

Between 2000 and 2018 in Denmark, 2.2 million m^2 of residential buildings are constructed annually (Statistics Denmark, 2019). Of these, 71% are of the types (single-family and terraced houses) in focus for this research (ibid.). The work of this dissertation shows a selection of strategies that manages to reduce embodied impacts by up to 40% from these building types compared with a reference building in a life cycle perspective. However, it is also clear from the emission profiles of the modelled buildings that the initial emissions of the constructions are far from the zero needed to comply with the global emissions targets. Low-carbon design strategies are needed to support the efforts in reducing emissions faster and more intensively towards 2050. This means that the low-carbon strategies employed by the sector should focus on reducing these initial emissions. In parallel, the harmonisation of methods should develop to meet the concerns about initial, and more certain, carbon investments, for instance by including the construction stage impacts (modules A4-A5) as part of the harmonised method.

IN-PRACTICE TARGETS - RELATIVE VERSUS ABSOLUTE

In general, the assessed buildings of the current dissertation perform well compared to the reference benchmarks of 6 kg CO_2e/m^2/year from Publication III (see the Aggregated embodied impacts in Figure 3). However, it must not become a habit for the building designers to settle with improvements of up to 40%. Although the reference benchmarks may support the general perception of what low-carbon design can achieve, the comparison is still just made relative to the current building practice. Current building practice is not by any means tailored to reduce carbon emissions, other than as a side effect of saving costs via savings of energy and resources. A different type of benchmarking practice exists via the top-down benchmarks that are typically based on political targets, for instance the 2-degree target of the Paris Agreement, (Hollberg et al., 2019). The top-down targets are based on a ‘carbon budget thinking’, in which the defined budget is distributed via chosen sharing principles. Existing literature on building LCA have taken point of departure in the carbon budgets suggested by Röckström et al. (2009) as part of the concept of planetary boundaries (Brejnrod, Kalbar, Petersen, & Birkved, 2017; Ohms et al., 2019). These studies show how average, new single-family buildings overshoot the allocated carbon budget by approximately a factor 10.

With a net zero target in the horizon, it becomes clear that a single design strategy will not do the job alone. Hence, there is a need for effectively combining all low-carbon strategies for the construction needs that cannot be realised otherwise. The strategies will have to form part of a larger effort to transition the human consumption patterns towards net zero. Probably in a mixed effort of technology development in combination with an agenda of sufficiency and immediate savings of energy and resources (Alfredsson et al., 2018, Lovins et al, 2019).

The current use of reference benchmarks in certification systems and regulation represents an eco-efficiency approach in which every product unit (in this case a square meter of building over a lifecycle of 120 years) is aimed at having a reduced impact (e.g. 40%) compared to the reference. However, this approach of reducing impacts per product unit is equivalent to the energy-efficiency approach that has governed the European movement towards energy-efficient housing within the past two decades. It bears the risks of rebound effects that counteracts the intended purpose, popularly known as Jevons paradox (Sorrell, 2009). For instance, Danish energy use in residential buildings has been reduced with 45% since 1975. However, the total energy use in Danish residential and office buildings have remained on the same level for 25 years, reflecting an overall growth in the building stock (Ingeniøren, 2018). The current approach of reference LCA benchmarks per m^2 as guiding values should thus be perceived as a step on the way towards minimising the impacts from building construction in a gradually more confined space for carbon emissions. To track the development properly within the restricted carbon budget, additional top-down, budget-based indicators and benchmarks should be introduced.

SYSTEM VERSUS PRODUCT PERSPECTIVE

Publication II explores how the allocation practice in the European standards does not credit, in full, the merits of a product cascading. The EN 15978/15804 allocation can be characterised as risk aversive, in the sense that focus is placed on current emissions and follows the ‘polluter pays’ principle (Frischknecht, 2010). However, the product focus of the European standards should not divert attention from the fact that every production, use and disposal of a building is interconnected with a myriad of other systems and processes outside the defined system boundaries. This extended system perspective is relevant for circular economy projects in which a core theme is the closing and prolongation of material loops.

The product focus supports a view of the world in which human activity and its exchanges with the environment are assessed piece by piece. This product focus aligns well with the value-chain perspective of a building product manufacturer or a building owner. In a societal perspective, however, the interdependencies between single product systems are important to know in order to support decisions that improve the performance of the larger system. Hence, the different actions for a zero carbon future need supplementary evaluations at an enlarged system’s scale. Within the concept of life cycle thinking, these system scale evaluations can be performed as consequential assessments (Ekvall & Weidema, 2004; European Commission - JRC, 2010). An example of necessary, enlarged system scale evaluations concerns the general increase in demand for bio-based materials – not only for the building sector, but also for packaging, fuel etc. For a low-carbon future in which biomaterials are perceived as being ‘CO_2 neutral’, there is a risk that the general demand may overtake the regeneration rate of the forest stock. This may then lead to unintended consequences in marginal production, for instance via clearance of rainforest.

Unintended consequences may also pertain to a single-eyed focus on GWP. Several characterisation methods are available in LCA for assessing different types of environmental impact potentials, toxicological potentials, resource uses etc. GWP of building LCAs correlates strongly with the use of fossil fuels and primary energy and to some extent with other environmental impacts such as acidification potential (Marsh, 2016). However, a broader scope of categories is needed to address (eco-)toxicological impacts as well as land-use-changes (Lasvaux et al., 2016; Laurent et al., 2012). Within the current focus on GWP it should not be forgotten that there are more environmental areas of protection that need further exploration in relation to the chosen low-carbon strategies.

Additionally, other types of system accounting exists that transcend the anthropocentric viewpoint and evaluate systems based on their thermodynamic qualities, e.g. exergy and emergy accounting (Brown & Herendeen, 1996; Odum, 1988). Although these accounting methods are, to some extent, compatible with the LCA method (see e.g. Raugei, Rugani, Benetto, & Ingwersen, 2014), they represent a broader, ecocentric perspective of systems thinking that has not been adopted by the building sector in practice.

SUMMARY - A FRAMEWORK FOR BUILDING LCA IN PRACTICE

The discussion presents three core aspects pertaining to the assessment context for Danish building LCAs. The temporal perspective of the net zero future is of utmost importance to keep in mind for the future development of LCA method as well as the design practice. This implies a more prevalent focus on the emissions related to the initial construction of the buildings. Closely related to this is the second aspect: the current focus on relative performance values should be supplemented with a focus on a budget-approach to the remaining emissions ‘allowed’ within the confined space of emissions towards 2050. The third aspect concerns the societal context within which the building sector is embedded. While buildings and building products within the sector may be optimised to comply with shrinking carbon budgets, there is a need for continuously evaluating how the larger system is progressing towards the set targets. This requires a cross-sectoral, multi-disciplinary effort that involves more than the eco-efficiency approach implemented in the current Danish LCA practice for buildings.

The framework in Figure 12 visualises the dynamics surrounding the current Danish practice of low-carbon design in method and practice. These dynamics contribute to explaining why it can be difficult transferring the low-carbon design strategies, which have proven successful in one context (e.g. national or regional), into a different setting. The centre of the framework concerns the current practice, i.e. how buildings are built and how the LCAs are carried out. The findings of the current dissertation address these issues on a direct level, recognising that progress is made in an interaction between the specific initiatives and the method/data/tools used for assessing the environmental viability of these initiatives. The initiatives, the method/data/tools as well as the practice is shaped by the sectoral context, i.e. the regulation, standards and trends characterising the focus of the national building sector. The sectoral context itself is affected by the surrounding societal context, i.e. bordering regulations, trends and targets. The framework in Figure 12 illustrates that even though robust evaluations of low-carbon design strategies can be found for the current practice, there is a whole range of influencing parameters, at different levels, that may gradually change the context. The changes of context may necessitate reconfiguration of the practice for building design as well as for assessment practice.

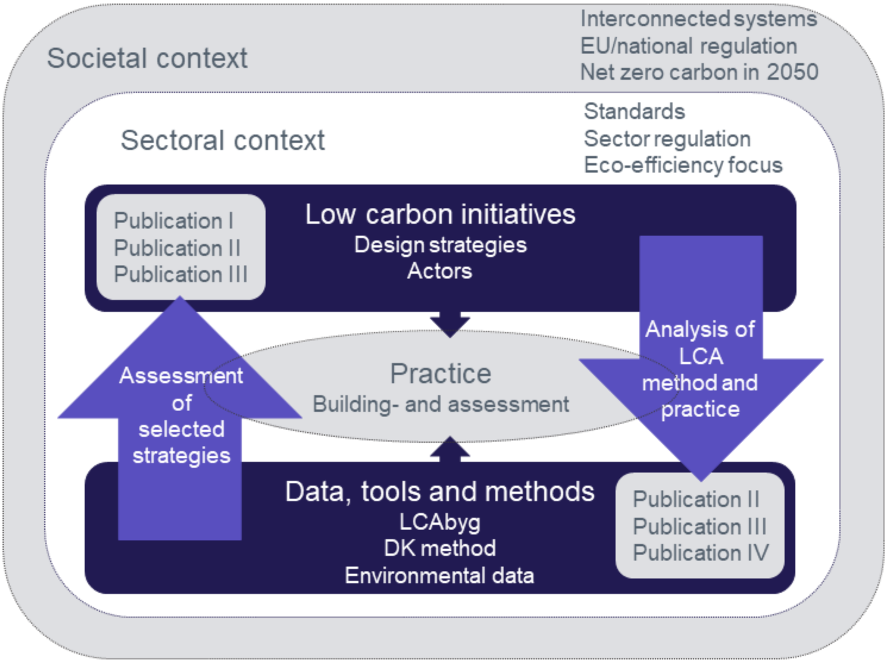


Figure 12. Framework representing the dynamics of low-carbon strategies, assessment methods and practice, taking place within the context of the sector and/or the society as a whole. Blue arrows represent the two focus areas of the current dissertation: Analysis of LCA method and practice, and Assessment of selected strategies.

CHAPTER 6. CONCLUSIONS

This dissertation has provided the Danish building sector with embodied GHG profiles of five low-carbon design strategies applied in practice. Further, the dissertation has clarified how the context of practice affects the building LCAs that are carried out. The main research question and the four sub questions are recapped here, the main question synthesising the findings from the sub questions:

Main research question: How do selected low-carbon design strategies contribute to solving the climate challenge of the building sector when evaluated according to Danish assessment practice?

Notable GHG savings of up to 40% can be achieved by applying the design strategies that have been tested in current Danish building practice. Gradually improving the current building practice may partly find its use in the coming decade where Danish GHG emissions are to be reduced by 70%. However, current Danish assessment and building practice is, put bluntly, off target in relation to the net zero emission future advocated by climate scientists. The research in this dissertation unveils the context related preconditions that affect the current assessment practice in Denmark, and presents a framework for understanding the dynamic relations between practices, method and specific initiatives. The surrounding sectoral as well as the societal context influence the practices. Hence, a reconfiguration of the societal targets toward a net zero future necessitates a reconfiguration of the strategies and assessment methods applied in the Danish building practice. Further development of assessment methods must strive for an approach that acknowledges the urgency of reducing emissions of today, for instance by including more of the current life cycle stages in the method and by adopting a benchmarking system based on the remaining carbon budget. A large-scale effort is needed to identify and implement strategies that will bring society to net zero emissions. For the building sector, this concerns not only the construction of new buildings, but also the way existing buildings are renovated and the way they are used. In summary, current low-carbon building practice is a mere step on the way towards a building sector in sync with the planetary boundaries for GHG emissions, and the development of design strategies as well as carbon-assessment methods, need intensive advancements in the forthcoming years.

What is the embodied carbon in examples of design strategies applied in Danish building practice?

To answer this, five buildings, representing four different low-carbon strategies from current practice were compared with a typical reference building. Recycling proved to be an effective design strategy for low-carbon housing with a saving potential for embodied carbon of around 40% compared to a typical single-family building inducing 4.9 kg CO_2e/m^2/year over a 120-year reference study period. Designing for a long service life of materials yielded saving potentials within the same range, although this potential is much dependent of the set scenarios. The example of a design for adaptability entailed less saving potential and was much dependent on the set scenarios. There may be life cycle benefits in a strategy about designing for low energy consumption. However, the modelled decarbonisation of the energy system significantly influences these potential benefits. A design for disassembly in a terraced house proved to entail an increase of embodied carbon compared to the reference, although there may be benefits in a wider systems perspective. Additional strategies, e.g. concerning bio-based and less processed materials, as well as combination potentials between the strategies should be further investigated to identify the extent of potential reductions by current practice as well as niche design initiatives.

What is the level of reference for the embodied carbon of new residential buildings in Denmark?

A derivation of preliminary reference values for Danish multi-family and residential buildings was carried out. The median embodied carbon profile was found to be 6.0 kg CO2e/m2/year over a 120-year reference study period, i.e. 20% higher than the carbon profile found for the typical single-family building in Publication I. This reference benchmark should be perceived in light of the limited sample size (seven buildings) and the potential bias concerning key contributing building elements, in this case the roof constructions. The benchmarking process should thus be repeated regularly to ensure representativity of buildings and data.

How does the Danish assessment practice for building LCAs align with general principles of LCA?

This research shows how the assessment and benchmarking practice is shaped within a constellation of actors and contextual preconditions. The resulting assessment and benchmark system may be broadly accepted within the sector, but reflects a pragmatic approach to the general principles of, for instance, representativity and comprehensiveness. Hence, the method applied in practice contains a range of trade-offs, e.g. limitations of included life cycle stages, which ensure ease-of-application but impede the comprehensiveness and thereby the credibility of the assessment results.

Which method-related drivers affect the outcome of building LCAs?

Through a systematic mapping of method-related drivers from theory and practice, a range of important parameters was identified. The parameters encompass differences in goal and intended use of study, lack of universal definitions, variation in study period and system boundary as well as a number of variations connected to the background environmental data used for assessments. The listed parameters (in Table 5) are recommended to serve as points-of-attention to ensure transparency of studies. Further, the development of assessment methods for the Danish practice should use the points-of-attention to cross validate whether the outcome of a chosen methodological approach may be sensitive to alternative choices.

FUTURE RESEARCH

Future research within the field of methodological drivers should investigate to which extent the multiple varying parameters affect the numerical results of a building LCA.

Future research within the field of practice-based drivers should elaborate on the socio-technical aspects of developing and applying the LCA method, and how best to implement the ambitious GHG reduction targets within the assessment practice.

Future research within the field of benchmarks should broaden the sample size, as well as specifying benchmarks based on the type of buildings to ensure representativity. Furthermore, the introduction of additional indicators reflecting a top-down approach is advisable, to assist in the future efforts of staying within the limited carbon budgets.

Future research within the field of low-carbon strategies for implementation in practice should expand the selection of assessed strategies. Furthermore, research should systematically combine the effective strategies to obtain the most viable saving potentials in light of the emission timing and emission budgets.

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APPENDICES

Appendix A. Publication I

Publication I: **Low-carbon design strategies for new residential buildings – lessons from Danish architectural practice.** *Rasmussen, F; Birkved, M; Birgisdóttir, H.* Submitted to Architectural Engineering and Design Management, 2020

Low carbon design strategies for new residential buildings - lessons from Danish architectural practice

This study presents the environmental life cycle assessment of four low carbon design strategies applied in Danish, architectural practice. The subject of analysis is a set of five buildings erected within the same constrictions in terms of floor area, operational energy performance and construction costs. Each of the design and construction teams followed specific strategies targeting four different themes: the use of recycled materials, design for extended durability of components, adaptable design, and design for reduction of operational energy demand. The results of the five buildings are compared with a reference building (i.e. a typical, Danish single-family dwelling). Results show that the recycling/upcycling strategy is the most effective in reducing the embodied carbon of a single-family dwelling. The use of structural wood in the same design furthermore points to the use of wood as a viable strategy for improving the carbon footprint of buildings –assuming that the biogenic carbon content of the wood can be considered carbon neutral. In combination, these two strategies result in an approximate 40 % saving of life cycle embodied carbon compared to the reference building. The design strategy of using durable materials yields up to 30 % lower embodied carbon compared to the reference building, whereas a design for adaptability results in 17 % lower embodied carbon relative to the reference building. However, these strategies are sensitive to the scenarios made for the service lives of materials and the implemented disassembly solutions. In a life cycle carbon perspective, the emissions from energy use in the building prove to be of importance, although there are notable differences depending on the modelling approaches of the energy mix. With the shrinking, global carbon budgets in mind, there is justified reason, not just to apply the most efficient of the assessed strategies, but to holistically optimize the design of new buildings by integrating various design aspects addressing the whole life cycle of the building.

Keywords: embodied carbon; life cycle assessment; building design; mitigation strategies, carbon budgets

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Introduction

Low carbon building design denotes the concept of minimising greenhouse gas emissions from the life cycle of the building, and is a concept receiving increased attention in recent years from building research, practice and policies (Pomponi, De Wolf, & Moncaster, 2018). For decades, reductions of operational carbon have been in focus, for instance via the European Energy Performance in Buildings Directive (EPBD), resulting in all European Union countries addressing the issue at an ambitious level.

Research has previously pointed to the shifting energy balances of the life cycle stages in new constructions with low operational energy demands (see e.g. Feist, 1996; Sartori & Hestnes, 2007). Recently, the near-zero energy building (NZEB) concepts for new buildings and retrofits have also brought the challenge about embodied environmental impacts in focus, since the accumulated impacts from limited (or zero) energy use are superseded by embodied impacts associated with production, replacements and end-of-life (EoL) treatment of materials (Blengini & Di Carlo, 2010; Georges, Haase, Houlihan Wiberg, Kristjansdottir, & Risholt, 2015; Lützkendorf, Foliente, Balouktsi, & Houlihan Wiberg, 2014; Rasmussen & Birgisdóttir, 2016b).

Countries, organisations as well as policy-makers have taken up the theme of embodied impacts in strategies and specific initiatives (Lützkendorf, 2017). In parallel, European as well as international standards offer a common, specified framework for life cycle assessments of buildings (CEN, 2012b; ISO/TC 59/SC 17, 2017). The multitude of initiatives indicate that there is a growing awareness of the need to address the embodied impacts associated with the built environment.

In Denmark, an increasing number of building designers attempt to incorporate LCA perspectives in their integrated design (Landgren, Jakobsen, Wohlenberg, & Jensen, 2018). However, since no regulation on the topic is in place, the incentive to integrate LCA mainly relates to the building certification schemes requiring it, such as the DGNB scheme (Danish Green Building Council, 2016). In a series of interviews with Danish practitioners, Sørensen et al. (2020) showed how design practitioners address the environmental perspective of design solutions based on experience from earlier projects where LCA have been in focus. Only few companies have the sufficient in-house LCA expertise to apply LCA consistently on their building projects (Sørensen et al., 2020), and the application of existing low carbon strategies, from outside the company, is thus potentially useful.

Existing research include several individual case studies in which design options are tested, although, in general, only one design parameter is evaluated at a time, e.g. using bio-based materials (Salazar & Meil, 2009; Sodagar, Rai, Jones, Wihan, & Fieldson, 2011), design for disassembly (Tingley & Davison, 2012; Eberhardt, Birgisdóttir, & Birkved, 2018) or design for low operational energy use (Kristjansdottir, Heeren, Andresen, & Brattebø, 2017). However, the single case study examples apply different methodological approaches in the LCA. This means that it is challenging, if not impossible, to use individual case studies, to determine which strategies are most efficient in achieving low carbon building designs (Malmqvist et al., 2018).

There are also examples of design strategies evaluated on the basis of larger samples of existing buildings. For instance, De Wolf (2017) evaluated different design strategies for low carbon structural design of existing buildings. A large-scale Norwegian research project evaluated the different pathways to achieving ‘zero emission buildings’ of different levels of ambitions (Wiik, Fufa, Kristjansdottir, & Andresen, 2018). The larger sample sizes of these studies ensure a harmonised methodological approach although the assessed buildings vary notably as functional entities, e.g. in terms of type, size and location.

In summary, there is a knowledge gap regarding similar types of cases from architectural practice presenting various low-carbon design strategies and assessed by use of comparable methodological approaches.

In 2013, the five MiniCO$_2$ houses were planned and erected as a demonstration project in Nyborg, Denmark. The project aimed at demonstrating how CO$_2$ reductions in the built environment can be carried out via focus on different life cycle stages of the building. Realdania By & Byg, a subsidiary of the Realdania philanthropic organisation, funded the design development and set a common framework for the buildings concerning size (135-150 m^2 floor area – housing for a family of four), construction costs, and operational energy performance of the buildings corresponding to the 'low-energy' building code 2015 (The Danish Transport and Construction Agency, 2015).

Due to the similar outset of the five MiniCO$_2$ houses concerning, location, size and costs, they represent an opportunity to evaluate real examples of applied low carbon design strategies within the Danish context of building and assessment practice.

The following research question serves as the backbone of the paper's analyses:

- How do the design strategies of the five MiniCO$_2$ houses, targeting four different life cycle stages, perform in life cycle and embodied carbon emissions against a reference building design?

The assessments of the buildings are carried out applying a consistent methodological framework used in the Danish assessment context, and thus provide examples of how well each design strategy performs in comparison to a traditional new-built dwelling. The focus of the five MiniCO$_2$ houses and the Reference House are displayed in Table 1. Table 1 also displays the low carbon design initiatives employed by the design teams of the different buildings.

Table 1. Details of the six assessed buildings

Case building	Upcycle House	Maintenance Free House (MFH)		Adaptable House	Quota House	Reference House
		Traditional	Innovative			
Size, GFA (m^2)	134	136	139	146	141	150
Structural principles	Structural frame by use of two 40 feet high cube containers. Wood-based floor and roof constructions. Steel-screw foundation	Load-bearing brickwork in exterior and core inner walls. Concrete slab and wood-based roof construction. Concrete strip foundation	Pre-assembled wood-framed modules coated with tempered glass. Inner concrete core around bathroom. Concrete well foundations	Load-bearing external walls of aerated concrete blocks in two storeys. Built-up roof. Concrete strip foundation	Load-bearing external walls of aerated concrete blocks in one storey. Built-up roof. Concrete strip foundation	Load-bearing external walls of concrete-mineral wool – brickwork. Concrete slab and wood-based roof construction. Concrete strip foundation
Core CO_2 minimizing focus	Reduction of embodied emissions from materials from construction	Prolongation of service life of materials and building, thereby reducing embodied emissions from replacing materials in the building's use stage. Employing a traditional architectural expression	Prolongation of service life of materials and building, thereby reducing embodied emissions from replacing materials in the building's use stage. Employing an innovative architectural expression	Reduction of embodied emissions from materials used for refurbishing/expanding building.	Reduction of operational emissions from energy consumption in the building's use stage	None intended
CO_2 minimizing design initiatives	Sourcing second-hand/reused materials, e.g. EPS from packaging waste, steel container from shipping industry, windows discarded by manufacturer Sourcing building materials with large fractions of recycled input , e.g. aluminium plate, gypsum boards, wood-plastic composite	Attention towards designing building envelope in homogenous, durable material (brick) to avoid construction layers with low service life. Designing with large overhangs that protect vulnerable elements (windows and doors) against wear and tear	Cladding of the structural frame in tempered, naturally ventilated glass. Designing with large overhang that protects vulnerable elements (windows and doors) against wear and tear	Interior design made with movable inner walls. Building envelope designed for disassembly, i.e. flexible for expansion with direct reuse of elements	Building design 'nudging' to low-energy behaviour, e.g. cooling chamber for food storage, roofed terrace for drying clothes Integrated 'smart' technology, e.g. self-regulating thermostats on radiators Built-in devices that creates awareness about consumption, e.g. showerhead that turns on a red light after 5 minutes of showering.	None intended
						

Materials and methods

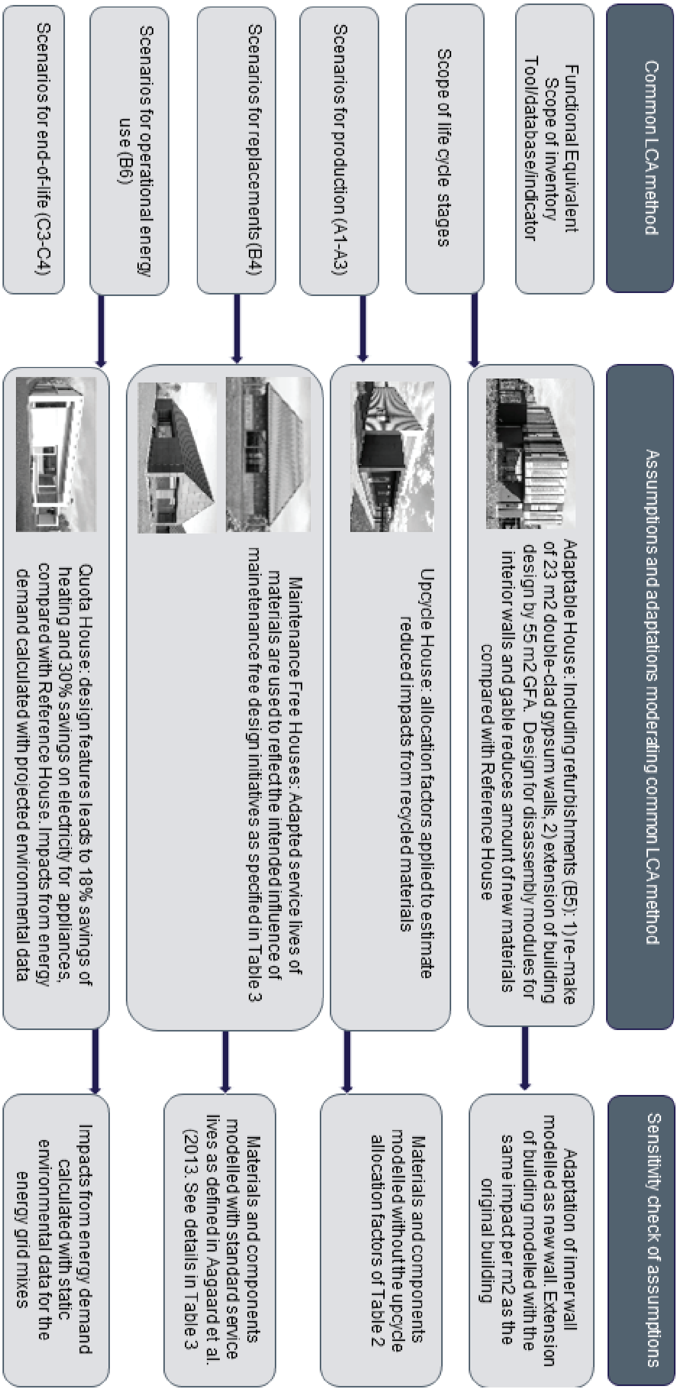
LCA is used as the core method to evaluate the carbon profiles, i.e. the life cycle greenhouse gas (GHG) emissions of the MiniCO2 houses. The goal of the LCA study is to use a commonly applied Danish LCA method to compare the MiniCO2 houses and their individual CO2 minimizing focus against a typical, Danish detached dwelling, the Reference House. The functional equivalent is expressed by 1 m2 gross floor area (GFA) per year of building service life, which is set as 120 years for all buildings. This functional equivalent is chosen because it is the functional equivalent prescribed by the common, national approach described in the following.

The LCAs of the buildings are carried out with the methodological approach developed as part of the national adaptation of the DGNB certification scheme for sustainable buildings. This common method, based on the EN 15978 standard, was collaboratively developed by the Danish Green Building Council, the building authorities, industry stakeholders and research bodies (Birgisdóttir & Rasmussen, 2019; Danish Green Building Council, 2016; Rasmussen & Birgisdóttir, 2016a). The common LCA method specify core methodological choices such as the functional equivalent, or the service life of materials on a general level. However, the general method was adapted for this research in some areas to assess the attributes of the different MiniCO$_2$ houses' designs. The common LCA method and the adaptations used in this study are illustrated in Figure 1 and described in detail in the following sections. Figure 1 further specify the sensitivity checks used to evaluate the assumptions for the MiniCO$_2$ Houses.

Common LCA method

Scope of inventory

All building materials and main technical equipment for the buildings are modelled as declared by the design teams. Inventories were manually checked for consistency and eventually validated by the design teams. The inventory scope reflects the assessment practice of Danish building LCAs as expressed in the Danish adaptation of the certification scheme DGNB (Danish Green Building Council, 2016). The scope covers foundations, frame, external walls, doors and windows, internal walls, staircases, roof, floor, ceiling, and central, technical aggregates. The inventory does not include connective items (e.g. screws and nails) nor technical distribution systems due to the cut-off rules of EN 15978 and the Danish adaptation of the DGNB LCA method (CEN, 2012b; Rasmussen et al., 2019). Detailed inventories can be found in supplementary material.



Common LCA method	Assumptions and adaptations moderating common LCA method	Sensitivity check of assumptions
Functional Equivalent Scope of inventory Tool/database/indicator		
Scope of life cycle stages	Adaptable House: Including refurbishments (B5): 1) re-make of 23 m2 double-clad gypsum walls, 2) extension of building design by 55 m2 GFA. Design for disassembly modules for interior walls and gable reduces amount of new materials compared with Reference House	Adaptation of inner wall modelled as new wall. Extension of building modelled with the same impact per m2 as the original building
Scenarios for production (A1-A3)	Upcycle House: allocation factors applied to estimate reduced impacts from recycled materials	Materials and components modelled without the upcycle allocation factors of Table 2
Scenarios for replacements (B4)	Maintenance Free Houses: Adapted service lives of materials are used to reflect the intended influence of mainetenance free design initiatives as specified in Table 3	Materials and components modelled with standard service lives as defined in Aagaard et al. (2013. See details in Table 3
Scenarios for operational energy use (B6)	Quota House: design features leads to 18% savings of heating and 30% savings on electricity for appliances, compared with Reference House. Impacts from energy demand calculated with projected environmental data	Impacts from energy demand calculated with static environmental data for the energy grid mixes
Scenarios for end-of-life (C3-C4)		

Figure 1. The methodological set-up of current study: The common LCA method, the adaptations/assumptions and the sensitivity check of these assumptions.

Tool, database and indicator

The LCAbyg tool (Birgisdóttir & Rasmussen, 2019) was used for modelling of the buildings. The tool uses on the Ökobau 2016 database which is a database that provides environmental impact potentials from pre-defined flows of specific building products and materials (Gantner, Lenz, Horn, von Both, & Ebertshäuser, 2018). The allocation of product and emission flows between systems follows the 100:0 method as implemented in Ökobau 2016 in accordance with the EN 15804 standard (CEN, 2012a)

The impact category used for expressing the carbon profiles of the buildings is the Global Warming Potential (GWP_{100}), expressed in kg CO_2 equivalents (CO_2eq) as found in the Ökobau 2016 database. The category refers to the characterisation method of CML-IA version 4.1, Oct 2012 (University of Leiden, 2012).

Scope of life cycle stages

Embodied impacts are assessed for all buildings, i.e. life cycle stages (modules according to the EN 15978 standard); Production (A1-A3), Replacements (B4), Waste treatment (C3) and Disposal (C4). These key life cycle stages for the embodied impacts constitute the scope frequently applied in assessment practice (see e.g. Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, & Birgisdottir, 2019) and is used in the common, national method.

Scenarios for production (A1-A3)

Data used for the production stage of building materials includes exchanges with the environment from extraction of materials, transport and manufacturing as specified in EN 15804 (CEN, 2012a).

Scenarios for replacements (B4)

Building products are assumed replaced at the end of their service life. The replacement step involves production of a new building product and EoL treatment of the displaced material. Default service lives of building products and materials under Danish conditions are taken from Aagaard et al (2013).

Scenarios for operational energy use (B6)

The common LCA method includes the calculation of impacts from operational energy use in the building. For the current study, operational impacts are only calculated for the Quota House, being the building with this particular design focus, and the Reference House for comparison. The carbon emissions from the provided energy are based on the Danish electricity mix and the national average of district heating respectively. These mixes are modelled to reflect the future development of the grids towards the adopted, political agreements for low-carbon energy supply by 2050. Figure 2 displays the projected carbon intensity of the two energy carriers as they have been modelled for the Danish authorities (COWI consulting, 2016).

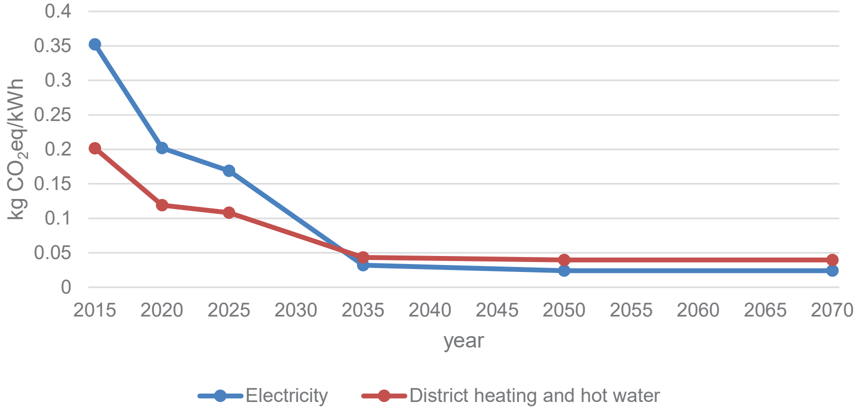


Figure 2. Modelled projection of the carbon intensity of the national Danish energy grids *(based on COWI consulting, 2016)*

Scenarios for end-of-life (C3-C4)

Data and scenarios used to calculate impacts from waste handling (C3) and disposal (C4) correspond to standard Danish practice at the material level.(Birgisdóttir & Rasmussen, 2019).

Adaptations of common LCA method

In this section, the assumptions and adaptations of the common LCA method are presented in detail for the individual building designs of this study. The assumptions are based on the design teams' own expectations in terms of durability of components, in terms of adaptability of construction solutions, and in terms of the energy demand in the building. For the Upcycle House, the factors used for impact calculations are derived by the authors.

Adapted scope of life cycle stages: Refurbishments

Besides the life cycle stages included as part of the common LCA method, the Adaptable House and the Reference House furthermore include evaluation of a refurbishment (B5) scenario. In both cases, the refurbishment scenario involves 1) an interior re-make of room partitions of a total of 23 m^2 double-clad gypsum walls, 2) an extension of the existing building design by 55 m^2 GFA.. The Adaptable House is constructed in a modular concept with elements designed for disassembly. This leads to the assumptions that a lower amount of materials are needed for the refurbishment actions in the Adaptable House than in the Reference House. Details on the specific material amounts can be found in the supplementary material. It is assumed that the buildings, after refurbishments, provide the same function as earlier, i.e. housing of a family of four.

Adapted scenarios for production: Upcycle allocation factors

For the Upcycle House, production data are modified to reflect the reused/recycled content of materials. This modification is applied due to data gaps in the life cycle impact assessment data used for the upcycled materials, i.e. the aggregated impacts from processes taking place between the end-of-waste state of the previous system and up to the production/re-manufacturing of the product in the building system under study (Rasmussen, Birkved, & Birgisdóttir, 2019). Two distinct approaches are made for these calculations depending on the recycling type being characterized as direct or indirect. Indirect recycling is here defined as a material being made from processed waste, thereby changing the original, physical properties of the recycled product. For the indirect recycling, environmental impacts are calculated based on the recycled content of the materials used, assuming that the recycled materials come practically burden free, save for some preparatory processes (e.g. shredding of the expanded polystyrene (EPS), see Table 2). Direct recycling is here defined as a material or component being sourced and used in its current form without a change in its physical properties, i.e. reuse. For the direct recycling of products or materials, no harmonised approach exists on how to adapt and allocate the environmental impacts (Eberhardt et al., 2018) In this study, economic allocation (based on the market prices of new and upcycled materials) is applied to distribute the impacts between virgin and recycled product. This approach is based on the work of Sander (2012). In this way, impacts of directly recycled materials are calculated from data on virgin material multiplied with an upcycle-factor that expresses the relationship between prices of the upcycled product and the total price of the material in a 2-loop system, i.e. where the virgin material is processed and sold in the first loop, then sold as upcycled material and later as waste material in a second loop. The upcycle factor is calculated as:

$$Fu = \frac{Pu}{Pu+Pi+Pw} \quad (1)$$

Where Fu is the upcycle factor, Pu is the price of the upcycled product, Pi is the initial price of the virgin product and Pw is the price of the waste after use (Sander, 2012).

Table 2 specifies the upcycle-factors used for the calculation of specific materials from direct and indirect recycling. Material recycling are, in some cases, e.g. aluminium or OSB boards, common industrial practice. Generic data of Ökobau can be expected to already incorporate the recycling benefits of those cases although documentation about this is limited. Hence, to avoid double counting of recycling benefits in current study, the upcycling factor is only applied to materials where direct/indirect reuse or recycling is judged *not* to represent common industrial practice.

Table 2. The calculation factors used to modify LCA data from virgin materials.

	Product/material		Upcycle factor of material production
Direct recycling (Sander, 2012)	Shipping container	Price of waste represents price of metal scrap waste	0.12
	Construction wood	Construction wood is primarily sourced from demolished buildings. The price of the reused wood is considered the same as the price of wood for incineration	0.14
	Windows	Upcycled windows are provided from flawed glass production that is being sold from the manufacturer to the design/construction team	0.12
Indirect recycling	Wood-plastic composite	This product is made of recycled paper 60 % and recycled polypropylene 38 %. Assuming recycled wood/plastic is burden-free. The factor is based on Sommerhuber et al. (2017) specifying the GWP contributions from virgin products to the wood-plastic-composite: HDPE (44%), wood particles (13%), leaving 43 % as process related impacts	0.43
	Gypsum boards	The selected gypsum board manufacturer operates production with 25 % of recycled input which is then considered burden-free	0.75
	Expanded polystyrene	Upcycled styrofoam is produced from discarded shock absorber product packaging. This production process requires only sorting and shredding of the Styrofoam. Impact is calculated based on impacts from energy mix use for shredding (specifications from shredder with the specifications of 8 kW, 350 kg EPS/h)	0.0078 kg CO_2eq/kg EPS

Adapted scenarios for replacements: Longevity of materials

For the Maintenance Free Houses, a set of adapted service lives are used to reflect the intended influence of maintenance free design initiatives as specified in Table 3.

Table 3. Number of replacements in the modelled Maintenance Free Houses (MFH) and the Reference House. Numbers in parentheses specify the number of replacements in the Maintenance Free Houses if following the service life table by Aagaard et al. (2013) used in the common LCA method.

	MFH Traditional	MFH Innovative	Reference House
Deck, insulation	0 (1)	0 (1)	1
Wall, insulation	0 (0*)	0 (1)	1
Wall, covering	0 (0)	0 (1)	0

Roof insulation	0 (2)	0 (2)	2
Roof covering	0 (1)	0 (1)	1
Window frames	1 (1)	1 (1)	1
Window glazing	2 (4)	2 (4)	4

* Not relevant, since the wall is constructed with a monolithic, insulating building system of fired clay blocks

Adapted scenarios for operational energy: Quota House

Impacts from operational energy use are calculated for the Quota House and the Reference House. In both cases, the energy demands for building operation are calculated by the engineering consultants of the Quota House (MOE engineers, 2016). The operational energy demand is calculated as the total demand for heating, hot water and ventilation in accordance with the mandatory thermal energy calculations of new residential buildings in Denmark (The Danish Transport and Construction Agency, 2015). The energy demand for the Reference House is modelled as 44.5 kWh/m^2/y of heating and hot water provision, and 2.6 kWh/m^2/y of electricity for building ventilation. In the Quota House, expectations based on the building design and technology, amount to a saving in heating of almost 18 % compared to the Reference House, resulting in an expected demand of 36.9 kWh/m^2/y of heating and hot water and 2.7 kWh/m^2/y of electricity for building ventilation. The thermal energy for all the MiniCO$_2$ Houses is provided by district heating supply.

Energy demand for the users' appliances is included in calculations of the Quota House and Reference House due to the building design of the Quota House aiming to also reduce this part of the energy use. Estimations of energy use for appliances are based on average consumption data for Danish households within the categories of entertainment, cooking, lighting, refrigerators, tumble drying, clothes washing, dishwashing and other (MOE engineers, 2016). For the Reference House, the electricity demand amounts to 3762 kWh/year. In the Quota House an expected saving of approximately 30 % results in an expected electricity demand of 2595 kWh/year.

Sensitivity check of assumptions

The sensitivity of a model in general describes the extent to which the variation of an input parameter or a choice leads to variation of the results (Rosenbaum, Georgiadis, & Fantke, 2018). LCA results are potentially sensitive to a range of uncertainty types, e.g. concerning data variability as well as parameter-, model-, and scenario uncertainties (Huijbregts, 1998). On a general level, there are two types of methods applied for sensitivity analyses in LCA: the local sensitivity analysis that determines the effect of a change in one of the input parameters at a time, and the global sensitivity analysis that determines the effects of parameters when these may vary over a significant range of uncertainty (Groen, Bokkers, Heijungs, & De Boer, 2017; Wei et al., 2015).

This study of the MiniCO$_2$ Houses is confined within the common LCA method as earlier described. Hence, it is not of immediate relevance to test parameter variations of, for instance, materials' service lives, because these are set as default boundary conditions of the current practice. However, this study challenges the common method in terms of the model adaptations and assumptions. Thus, to test the sensitivity of the conclusions drawn from these assumptions, a discrete check of the scenarios for each building was performed. This means that each of the MiniCO$_2$ Houses is modelled for a sensitivity check with the default, standard assumptions and calculation rules that form the base of the common LCA method (and of the Reference House model). The only exception from this is the sensitivity check of the Quota House that concerns the carbon intensity of the provided energy. Table 4 specifies how the building models are adapted for the sensitivity check.

Table 4. Modelling details of the sensitivity checks

Upcycle House	Materials and components modelled without the upcycle factors defined in Table 2
MFH Traditional	Materials and components modelled with standard service lives as defined in Aagaard et al. (2013). See details in Table 3
MFH Innovative	
Adaptable House	Adaptation of inner wall modelled as new wall. Extension of building modelled with the same impact per m^2 as the original building
Quota House	Impacts from energy demand calculated with static environmental data for the energy grid mixes

Results and discussion

The GWP in kg CO$_2$eq/m^2/year obtained for each of the five MiniCO$_2$ Houses and the Reference House are shown in Figure 3. The figure presents the contribution of the life cycle stages covered for each building and further highlights the life cycle stages that were targeted by the individual design strategies. For a comparison, the aggregated embodied carbon in Figure 3 denotes the scope of the life cycle stages calculated for all the buildings, i.e. the production (A1-A3), the replacements (B4) and the waste treatment and disposal (C3-C4).

The results presented for the Adaptable House furthermore includes GWP for refurbishment and the Quota House includes GWP related to energy use in the operational stage. The Reference House, being the building to which the other result sets are individually compared, include GWP from all life cycle stages covered by the study's LCA.

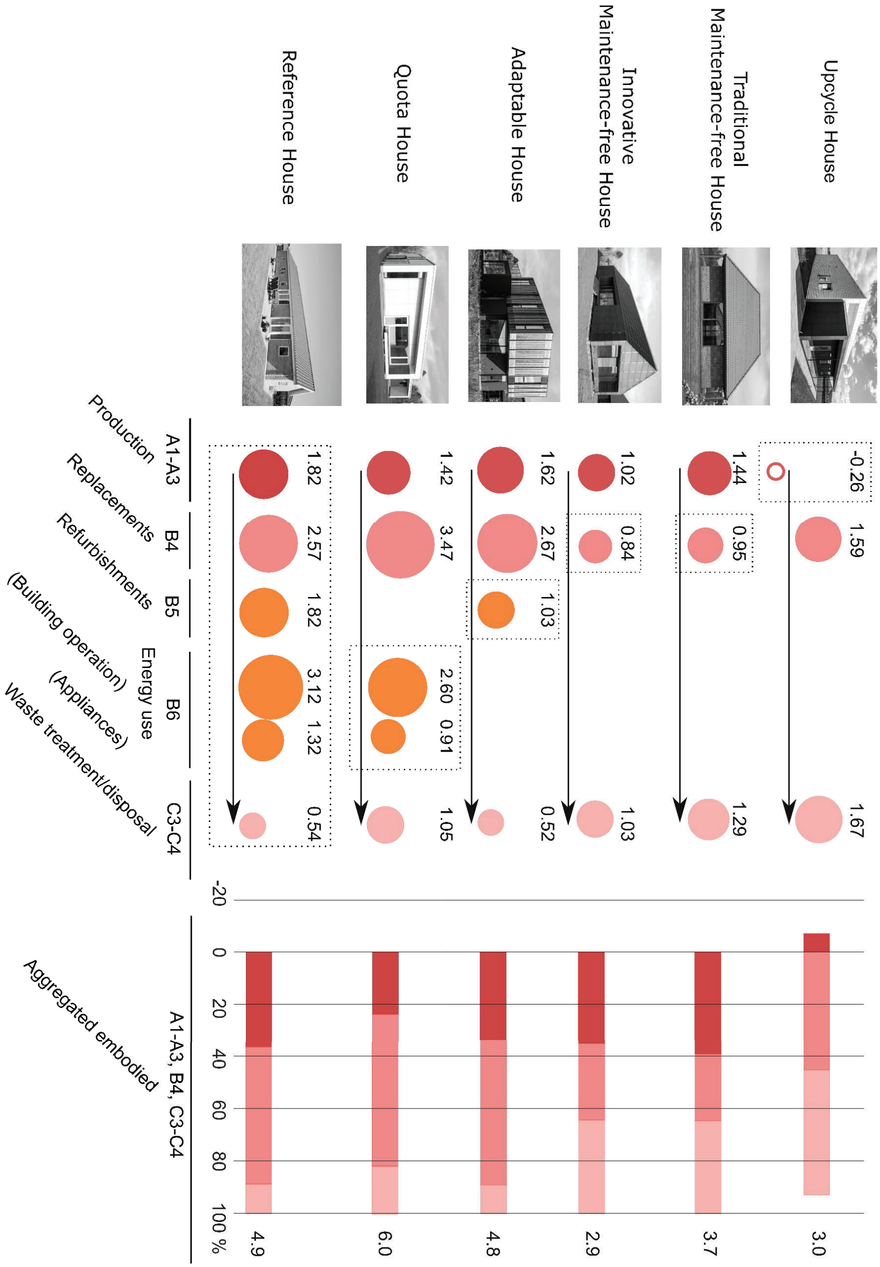


Figure 3. The GWP contributions in kg CO_2eq/m^2/year and percentages from the life cycle stages of the five experimental MiniCO$_2$ houses and the Reference House. The life cycle stage(s) in focus within each project is marked by the dotted lines.

Figure 3 presents how the production stage impact of the Upcycle House is lower than the production stage of the Reference House to the extent of actually presenting a net CO_2eq saving. The use of recycled materials contribute, as anticipated, to the low impact results of the building. However, the negative GWP is only possible due to the background database accounting for the storage of biogenic carbon in wood-based products. The stored carbon is emitted in the waste treatment stage, i.e. the eventual incineration, which explains why this life cycle stage of the Upcycle House is notably higher than that of the Reference House.

In the MFH Traditional and the MFH Innovative, the impacts induced by the recurring replacements of materials throughout the life cycle of the building are 66-70% lower than the baseline scenario for replacements (B4) represented by the Reference House. The assumptions made about durability of materials in the MFH's are a key parameter for the low impact profiles of these buildings. Thus, only half the number of window replacements are assumed necessary for the MFH's, due to the roof designs both integrating large overhangs to protect windows from wear and tear. Furthermore, the building envelopes, including the insulating layer, are assumed to endure for the same number of years as the building itself. This is not the case for the Reference House where the insulation is assumed to be replaced after a service life of 80 years in accordance with the Danish guidelines for replacements of building materials (Aagaard et al., 2013).

In the Adaptable House, the design for adaptability and disassembly ensures a potential GWP saving from the refurbishment stage (B5) that is 47% lower than that of the Reference House. The lower impacts from the Adaptable House reflect that the Adaptable House does not need additional materials for the rearrangement of inner walls, and only a limited amount of materials for the building extension is needed since the existing elements can be reused directly.

The Quota House is designed to nudge its residents towards a limited use of energy in relation to building operation (mainly heating and hot water) as well as for appliances (entertainment, cooking, washing etc.). Figure 3 reveals how the 2.6 and 0.91 kg $CO_2eq/m^2/year$ associated with energy use for building operations and appliances total an emission of 3.5 kg $CO_2eq/m^2/year$, which is 21% less than the total of the Reference House. On the other hand, the aggregated embodied carbon from the Quota House is 22% higher than that of the Reference House.

In-depth results and sensitivity checks

In the sensitivity checks of the MiniCO_2 Houses, each building is subject to a critical evaluation of its specific design strategy and the assumptions made for to the assessment.

Upcycle House

The design strategy applied for the Upcycle House targets the production stage of the building. Thus, a low-carbon profile is ensured by using recycled and upcycled materials that are partly burden-free (see Table 2 for the impact share in relation to virgin materials). Figure 4 presents how the composition of materials applied for construction of the Upcycle House and the Reference House are notably different. This material difference relates to the structural materials of the Reference House being of mineral origin (concrete and bricks) whereas the structural parts of the Upcycle House consists of recycled metal and wood. The cellulose-based insulation and wood used in the Upcycle House ensures a negative GWP from the production stage. The negative production related impacts are caused by the methodological approach within the background inventory data of bio-based materials: that they store biogenic carbon. The stored carbon is released at the EoL stage (incineration) of the materials and the aggregated embodied carbon of Upcycle House thereby amounts to 60 % of the corresponding figure for the Reference House.

In the sensitivity check of the Upcycle House presented in Figure 4, the materials are modelled without the impact reduction associated with the upcycling factors of Table 2. This means that all elements are modelled as produced from virgin materials. The associated impacts of the building are still notably lower than the Reference House although the contributions from the virgin glazing and steel components affect the GWP advantage of the production stage of the Upcycle House. Consequently, the aggregated embodied carbon of the sensitivity check model of the Upcycle House corresponds to 69% of the Reference House's life cycle embodied carbon. Hence, even with virgin materials there is a carbon saving from the specific design compared to the Reference House.

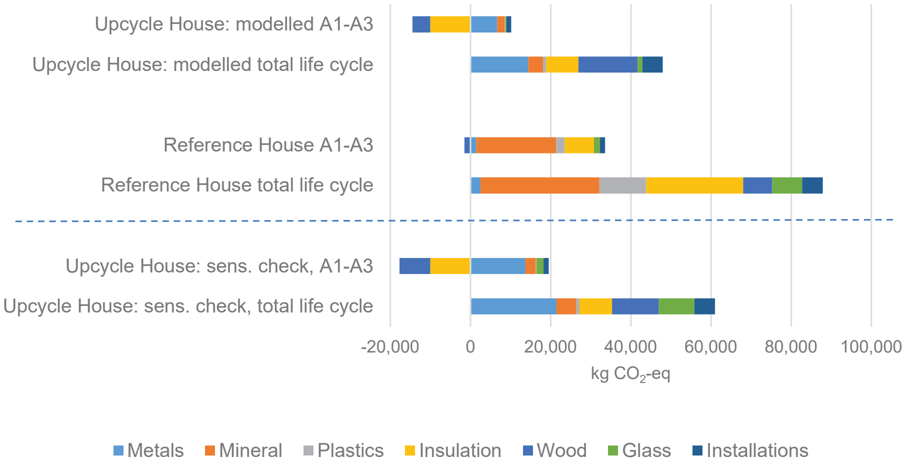


Figure 4. Details of Upcycle House with and without Upcycle-factors (refer Table 2).

The stored carbon plays an unmistakable role in the results of the Upcycle House. In the life cycle perspective of the Upcycle House, carbon neutrality is assumed, which means that the stored carbon in the production stage is balanced by corresponding emissions from the waste treatment, i.e. incineration (see Figure 2). In reality, the building design thus reflects the low-carbon benefits of recycling as well as the benefits of using wood based materials - under the specified assumption of carbon neutrality. In the research community, there are diverging approaches to the way stored carbon is included or excluded from carbon footprints of products (Brandão et al., 2013; Tellnes et al., 2017). Further, the simplified carbon neutrality assumption can be criticised for not properly taking into account the temporal significance of carbon fluxes from biomass growth, harvesting and degradation, which is related to the rotation time of the biomass growth (Cherubini, Peters, Berntsen, Strømman, & Hertwich, 2011). Additionally, the GWP impact category in LCA is an emission-based metric that does not include biogeophysical factors (e.g. the albedo-effect) contributing to global warming (Bright, Cherubini, & Strømman, 2012)

Maintenance Free Houses

For both Maintenance Free Houses (MFH), the focus of the design strategy is on longevity of the building and its components. Figure 5 reveals how, when applying the assumptions (see Table 3), the design strategy successfully achieves a reduction in life cycle embodied carbon of 26-30% compared to the Reference House. Figure 5 further pictures a sensitivity check for the MFHs without the assumptions about durability and longevity, i.e. applying standard, reference service lives of materials as modelled in the Reference House. In the sensitivity check, only the Traditional MFH performs better than the Reference House in a life cycle perspective. In this scenario, the Innovative MFH more than triples the impacts associated with replacement of materials. This remarkable change is caused by the more frequent replacement of materials of the building skin as well as replacements of the relatively larger window areas.

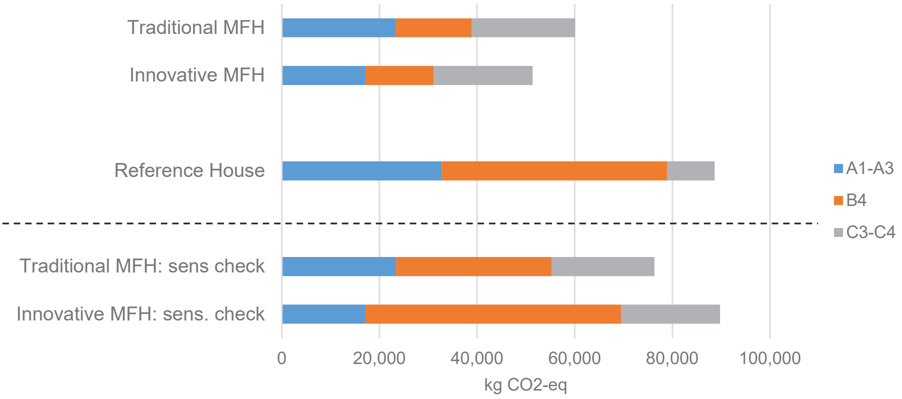


Figure 5. Details of the Traditional and Innovative MFHs and the Reference House.

Adaptable House

The design strategy applied for the Adaptable House focuses on the refurbishments occurring throughout the building's use stage. Figure 6 presents the impacts from the two defined refurbishment actions, i.e. rearranging internal walls and expansion of the existing building. The impacts associated with rearranging internal walls are burden-free in the Adaptable House. However, the action of rearranging internal walls constitutes only 2 % of the life cycle embodied carbon of the Reference House whereas the expansion adds a considerable share of 37 % to the life cycle embodied carbon of the Reference House. Due to the design for disassembly initiatives of the Adaptable House, the expansion corresponds to only 56 % of that of the Reference House, giving the Adaptable House an overall impact advantage of 20 tons CO_2eq, i.e. 17 % better than the Reference House if assessed in terms of life cycle embodied carbon from life cycle stages production (A1-A3), replacements (B4), refurbishment (B5) and waste treatment and disposal (C3-C4). In the sensitivity check, the advantage of the Adaptable House diminishes to perform only 4 % better than the life cycle embodied carbon of the Reference House.

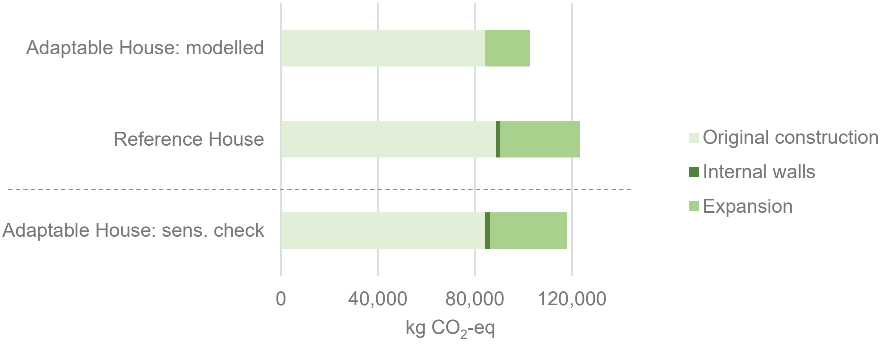


Figure 6. Details of the refurbishment actions modelled for the Adaptable House and the Reference House.

Quota House

Figure 7 displays details of the embodied and operational impacts of the Quota House and the Reference House calculated with the projected energy mixes of the common LCA method. In spite of the expected energy savings from the Quota House, the overall performance equals that of the Reference House, because the embodied impacts induced by the Quota House design are higher. The sensitivity check, also displayed in Figure 7, tests the results of the buildings modelled with a static energy modelling approach. A static energy modelling approach is prevalent international practice in building LCA although an ongoing decarbonisation of the energy systems is acknowledged (Röck et al., 2020). As seen from Figure 7, the life cycle carbon by modelling with the static approach is around twice the amount as calculated with the projected grid mixes. Further, in this case the Quota House outperforms the Reference House by inducing 17% less life cycle carbon. Thus, depending on the approach (i.e. static/projected) applied for the energy grid modelling, there may be notable impacts associated with operational energy demands for building operation and operating appliances. The uncertainties related to the future grid composition, thus highlight the difficulties associated with relying on lower operational energy demand as a viable low-carbon design strategy for buildings in itself. However, this is without considerations about new buildings using notable more energy for heating than modelled – the so-called performance gap (see e.g. Gram-Hanssen et al., 2018), which should be further investigated in terms of LCA.

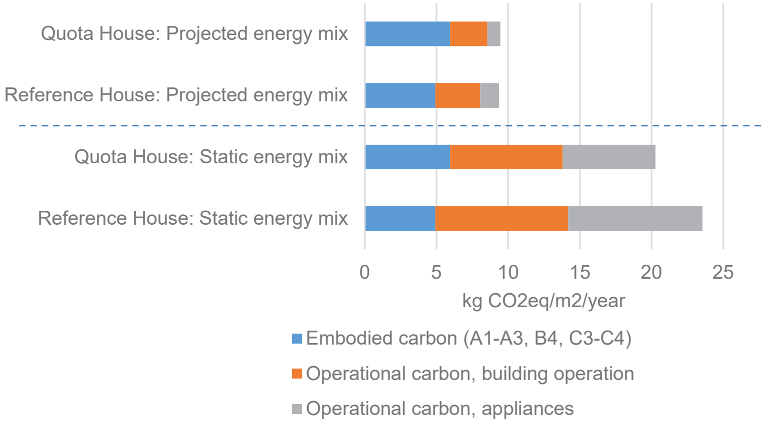


Figure 7. Details of the Quota House and the Reference House.

Critique of the functional equivalent

The MiniCO$_2$ Houses are all assessed with a long reference study period of 120 years. This long reference study period is prescribed by the common LCA method and reflects a balancing of functional, aesthetical, economic and technical service lives as described for Danish building types in Aagaard et al (2013). Even though a long service life may more genuinely represent the actual time that a residential building will serve its function, the long service life entails a higher level of uncertainty regarding the modelled scenarios of replacements and EoL.

Figure 8 explores the accumulated emissions from all buildings presented in this paper. For all buildings except the Upcycle House, considerable emissions – between 17 and 33 tons CO$_2$eq - occur in the year of construction. For each replacement taking place during the course of the life cycle of the buildings, additional impacts are induced by production of new materials. These replacement impacts are seen as the 'jumps' (mainly from year 20 to 100) made by the line graphs. These smaller pulses of additional emissions are especially notable halfway through the service life of the building. At the EoL treatment of the building materials after 120 years, another major pulse of emissions takes place. However, as noted earlier, the uncertainties related to these future emissions are profound and related to the processes defined for the waste treatment. Conversely, the impacts from construction of the building are far less uncertain because these emissions are taking place now. Hence, even though the life cycle perspective of the building is important to keep in mind, a parallel focus on the current carbon emissions from construction is imperative to avoid exceedance of the global carbon budget towards laid out by the International Panel on Climate Change in the Paris agreement (Rovers, Lützkendorf, & Habert, 2017). The significance of the construction phase is previously addressed in the literature (e.g. in Säynäjoki, Heinonen, & Junnila, 2012) and has additional relevance in light of the recent development of life cycle benchmarks being pursued in national and international contexts (Lützkendorf, 2017; Rasmussenet al., 2019). With this temporal focus in mind, the design approach of Upcycle House, i.e. using recycled materials with low impacts and/or bio-based materials with carbon storage, stands out as the preferable design option to pursue current low-carbon buildings. Future development of the common LCA method and its functional unit should incorporate this temporal perspective of the carbon emissions.

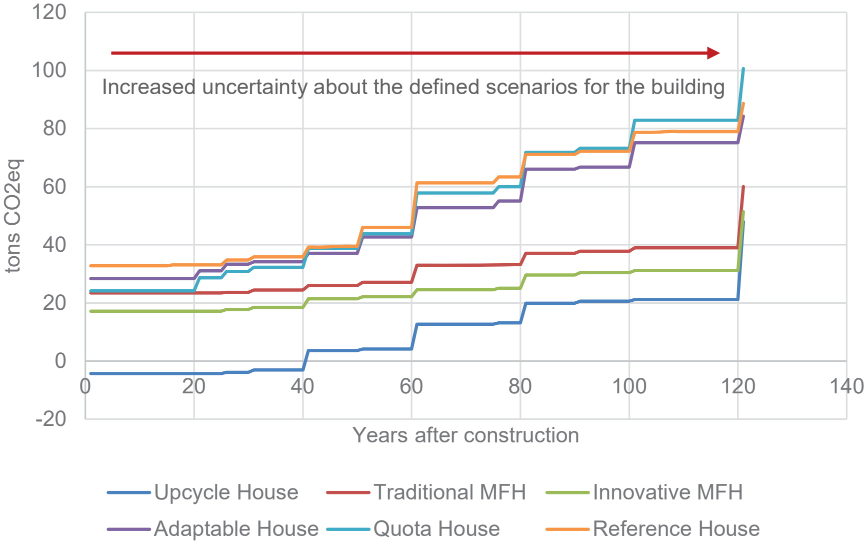


Figure 8. Accumulated carbon emissions from the production, replacement and end-of-life stages of the MiniCO$_2$ Houses and the Reference House.

Conclusion

This study assesses the carbon footprint of five residential stand-alone dwellings, the MiniCO$_2$ Houses, designed with four different low carbon strategies and compare these with the carbon footprint of a reference building. The study shows that the recycling/upcycling strategy applied in the Upcycle House is the most efficient in reducing the embodied carbon of a single-family building. The use of structural wood in the same design furthermore points to the use of wood as a viable strategy for improving the carbon footprint of buildings – under the methodological assumption that the wood is considered carbon neutral. In combination, these two strategies result in an approximate 40 % saving of life cycle embodied carbon compared to a reference, typical building. At the same time, both the recycling- and the wood-based material strategies address the temporal challenge of lowering GHG emissions immediately, and not only focusing on reductions in the long life cycle perspective of a building. Future research should elaborate on other types of allocation for the recycling and on the carbon fluxes related to the use of wood in the construction industry.

The design strategy of using durable materials reduces the embodied impacts up to 30 % compared to the reference, whereas a design for adaptability results in 17 % lower embodied carbon than the reference. However, these strategies are sensitive to the assumptions made for the defined service lives of materials and the disassembly solutions applied.

In a life cycle carbon perspective, the impacts from energy use in the building prove to be of importance although there are notable differences between the modelling approaches of the future energy mix. The viability of a design strategy targeting the users' energy demand thus proves dependent on the context of evaluation. Future research should look into the energy performance gap in new buildings to investigate its relevance to LCA results.

However, all of the assessed strategies; recycling, durability, adaptability and reduced energy demand, show potentials for notably reducing the climate burden of residential buildings. With the shrinking, global carbon budgets in mind, there is thus all the reason to, not just applying the most efficient of the assessed strategies, but to holistically optimize the design of new buildings by integrating various design aspects addressing the whole life cycle of the building. The cases of the current study provide real life examples of affordable design strategies and thus serve as inspiration for architectural practice focusing on low carbon emissions in the building life cycle.

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Appendix B. Publication II

Publication II: **Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies.** *Rasmussen, F; Birkved, M; Birgisdóttir, H.* In: IOP Conference Series: Earth and Environmental Science, 2019 (225)

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Upcycling and Design for Disassembly – LCA of buildings employing circular design strategies

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Abstract. Within the ReSOLVE framework, the concept of 'Looping' materials in an efficient way is a crucial theme to ensure environmental sustainability of circular economy. This paper investigates how current calculation practice of building LCA from the EN 15804/15978 standards affects the global warming potential (GWP) of building designs where material loops have been in focus. In this study, we calculate the environmental potentials of circular building design based on two cases; 1) a building constructed from primarily upcycled materials, and 2) a building constructed with principles of design for disassembly (DfD). Results from the two cases point to the significance of the EN standards’ allocation approach in which a system’s use of recycling/reuse is merited, rather than meriting a system providing recyclable/reusable materials. Hence, the upcycling strategy results in lower GWP, especially from the production stage, whereas the DfD strategy does not realize an environmental advantage within the framework of the EN standards. Results further shows that even though concrete elements are notable components of the DfD building, developing DfD-solutions for these exact elements might not be the preferred focus for optimizing the environmental benefits provided by the building. Instead, DfD focus could be on shorter-lived elements of high benefit potentials.

Keywords: Upcycling, Design for Disassembly, Circular Economy, Buildings, Allocation, LCA

1. Introduction

Circular economy has found a great appeal from business as well as research society as a concept for ensuring efficient use of resources. A comprehensive framework used for classifying circular approaches is presented by the ReSOLVE framework, which covers aspects of Regeneration, Sharing, Optimizing, Looping, Virtualizing, and Exchanging [1]. In the scope of the framework is thus a focus on the efficiency of resource provision (regenerate, loop) as well as a focus on the efficient use of resources (share, optimize, virtualize, exchange).

Life cycle assessment (LCA) has been in use for decades as a tool for documenting the performance of products and services by quantifying the related environmental impacts and resource uses. LCA is thus relevant in evaluating the circular efficiency of resources production and regeneration, because it enables pinpointing the preferable circular strategies to reduce environmental impacts [2]. The terminology of LCA reveals how the method already deals with product cycles, and the application potential of LCA for quantifying the looping aspect of the ReSOLVE framework is thus imminent.

Whereas general LCA guidance in accordance with the ISO 14040 series is given in the ILCD guidance [3], current European practice of building LCA is based on the European standards EN15804 and EN15978 [4][5]. These European standards reflect a long-term temporal perspective of buildings by focusing on single building systems - or loops - one at the time.

Central design strategies for looping in circular buildings are found in the concepts of 'upcycling' of materials and in the 'design for disassembly' (DfD), which represent the concepts of input circularity and output circularity to a building system. Some existing LCA studies deal with building design concepts of upcycling [6][7] and concepts of design for disassembly/reuse [8][9][10] with promising results on eco-efficiency potentials for both strategies. In the literature, however, the two concepts are treated as single cases with suitable allocation practices applied from case to case. Hence, there is a lack of literature showing how the two design concepts perform within the framework of a common allocation approach, such as the one defined in EN 15804/15978.

This paper investigates how current calculation practice of building LCA from the European standards affects the results of building design where circularity and material loops have been in focus. In this study, we calculate the environmental potentials of circular building design based on two cases; 1) a building constructed from recycled/upcycled materials, and 2) a building constructed with principles of design for disassembly (DfD). We discuss the allocation approach and its implications on results, and we point to the factors of the allocation that dis- and/or encourages the different ways of designing buildings with a focus on closing material loops.

2. Method

2.1. LCA modelling details of study

The functional equivalent of the studies are set as 1 m^2 of residential gross floor area per year.

The process-based LCAs of the two buildings include the following life cycle stages as defined in the EN 15978 standard: A1-A3 production of building materials, B4 replacement of building materials during use stage, C3-C4 waste treatment and disposal of materials at end-of-life. Furthermore, module D is included, however for the DfD building only. Module D expresses the net benefits and loads from the reuse, recycling and recovery of materials in the next product system. In effect, this corresponds to quantifying impacts and avoided impacts from the next loop(s) for the building materials. The benefits and loads are determined when materials leave the system under study at the replacement stage as well as at the building's end-of-life stage. All benefits and loads throughout the life cycle of the building are usually summed and reported in one single number as module D impacts.

Inventory system boundaries include foundations, structural frame, external walls, doors, staircases, internal walls, windows, roof, floor and ceiling. Technical systems and external works are not included. Neither are connectors, brackets etc. from the building elements. Inventory data originates from initial designs by the buildings' architects. Hence, only sketches of the buildings form the bases of the assessment, which means that amounts and types of insulation materials and windows are estimated for the DfD building.

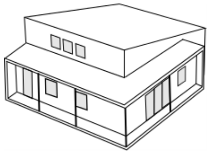
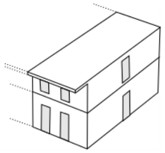
Both buildings are modelled in the Danish LCAbyg tool [11] that builds on a translated version of (mainly) generic LCIA data from the Ökobau database version 2016 [12]. The reference study period of the buildings is set to 120 years following the Danish guidelines on service lives of buildings [13]. Same report specifies the applied service lives for materials replaced during the use stage (module B4).

For reasons of simplicity only results of the indicator global warming potential (GWP) are reported in this paper.

2.2. Case study buildings

Details of the two buildings assessed for current study are summarized in Table 1. Note that for this study only embodied impacts are investigated, not operational impacts from heating and electricity. However, both buildings are constructed following the building class 2015 of the Danish building regulation, which means that the expected operational energy use is at identical levels.

Table 1. Details of case buildings.

	Upcycle building	DfD building
Type	Residential, single-family	Residential, multi-family
Heated floor area, m^2	129	77
Description of building	1-storey house with structural system of steel (shipping containers), light shell and built-up roof	2-storey apartment block concept of pre-cast concrete structure with a tile cladding shell and built-up roof
Upcycling/DfD strategies employed	Direct reuse of shipping containers as constructive elements. Direct reuse of concrete strip foundations, EPS, construction wood, windows and facing tiles. Material recycling of gypsum boards and aluminium	Elements designed for 2 service lives: constructive elements (concrete) designed for disassembly; façade system, gypsum and wood wool boards installed with rails and brackets; carpet tiles with take-back cleaning service and resale
Specification of 10 most prominent amounts of building materials (weight/volume)	102 m^3 Cellulose fibre ins. (45 kg/m^3) 159 m^2 Aluminium sheet for roof (0.7 mm) 5.9 m^3 Construction wood 200 m^2 Wood-plastic composite cladding 8000 kg Steel profile (shipping containers) 710 m^2 Gypsum boards (12 mm) 295 m^2 OSB boards (22 mm) 31 m^2 Windows (triple-glass) and frames 5 m^3 Facing tiles 6 m^3 Glass foam insulation	7.6 m^3 Concrete C50/60 (hollow core slabs) 6 m^3 Concrete C35/45 (ext. wall elements) 155 m^2 Tile for façade cladding (35 kg/m^2) 69 m^2 Wood wool boards (25 mm) 70 m^2 Carpet tiles, nylon 8.3 m^3 Expanded Polystyrene 30 m^3 mineral wool insulation (26 kg/m^3) 13 m^3 mineral wool, roof ins. (145 kg/m^3) 21 m^2 Windows (triple-glass) and frames 800 kg aluminium profile for façade system
Illustration of case building		

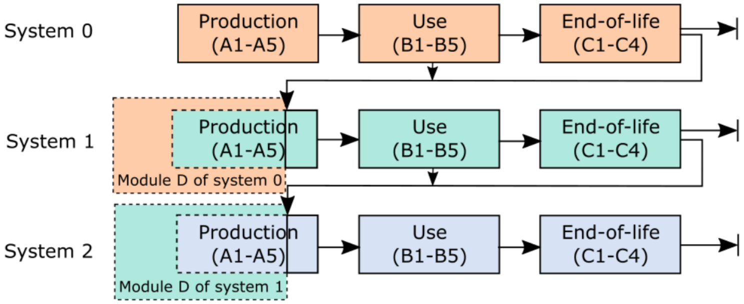


Figure 1. Principle of distribution in the 100:0 allocation approach of the EN 15804/15978 standards.

2.3. Allocation details in study

Allocation of impacts from production and end-of-life are calculated according to the 100:0 (or 'cut-off') approach of the EN 15804/15978. From this follows that environmental impacts are distributed as illustrated in Figure 1. In the case where system 1 is the assessed building, recyclable items (upcycled materials) from system 0 are burden free as input circularity to system 1, except for the processes of remanufacturing the materials. Recyclable items from system 1, i.e. output circularity (DfD) avoids production impacts in system 2, and these benefits for system 2 are reported as module D of system 1.

LCIA data gaps are present for the upcycled materials, i.e. the aggregated impacts from processes taking place between the end-of-waste state of the previous system and up to the production/re-manufacturing of the product in the system under study. Market prices of new and upcycled materials are used as proxy for estimating impacts associated with these processes. Hence, impacts of upcycled materials are calculated from data on virgin material multiplied with an upcycle-factor that expresses the relationship between prices of upcycled products and the total price of the material in a 2-loop system, where the material is sold initially in the first loop, then sold as upcycled and later as waste material in a second loop, i.e:

$$Fu = \frac{Pu}{Pu+Pi+Pw} \tag{1}$$

Where *Fu* is the upcycle factor, *Pu* is the price of the upcycled product, *Pi* is the initial price of the virgin product and *Pw* is the price of the waste after use [14].

Table 2 specifies the upcycle-factors used for the calculation of specific materials and products. Material recycling are, in some cases, e.g. aluminium or OSB boards, common industrial practice. Generic data of Ökobau can be expected to already incorporate the recycling benefits of those cases although documentation about this is limited. Hence, to avoid double counting of recycling benefits in current study, the upcycling factor is only applied to materials where direct reuse or recycling is judged not to represent common industrial practice. The end-of-life of upcycled materials in the Upcycle building are assumed parallel to regular Danish end-of-life practice [11].

Table 2. Upcycle factors of products and materials.

Product/material	Upcycle factor of material production
Concrete strip foundation	0.12
Shipping container	0.12
Expanded polystyrene	0.35
Construction wood	0.14
Wood-plastic composite	0.80
Gypsum boards	0.35
Window glass	0.12
Window frames	0.67
Facing tiles	0.10

Scenarios for the DfD elements of the DfD building are shown in Table 3 for the modelling of uses available in the next product system. The DfD products chosen for assessment are the products where producers, as part of the DfD building project, stated their products' potential for servicing two service lives. The materials for reuse are assumed to displace virgin-based products in module D at the percentage given in Table 3. Remanufacturing/adaptation processes of products at the start of their second service life are not taken into account in the calculations for this study.

Table 3. Scenarios for modelling of reuses of DfD elements. Scenarios for concrete elements are based on Eberhardt et al [9]. Other values are based on estimates.

Building element	Materials for reuse in 2nd system (%)	Service life per life cycle (years)
Concrete beams	80	120
Concrete roof hollow core slabs	60	120
Concrete floor hollow core slabs	90	120
Concrete walls	80	120
Façade system, battens, alu profiles	80	120
Façade system, clay tile	80	60
Wood wool ceiling boards	60	60
Gypsum wall boards	40	50
Carpet tiles	30	10

3. Results

Results of the global warming potential of the Upcycle building and the DfD building are presented in Table 4. Note that the Upcycle building construction is calculated in two versions, one (regular construction) covering the generic material data of the construction and the other where upcycle factors on materials from Table 2 are applied. The DfD building's results are calculated from generic materials data and present the benefits of next product system (module D) separately in accordance with the EN 15978 approach.

Table 4. GWP results of functional equivalence of the Upcycle building and the DfD building. Module D result of the DfD building is reported separately in parentheses.

Construction	GWP in kg CO_2-eq/m^2/year
Upcycle building – regular construction	4.7
Upcycle building – upcycled construction	3.6
DfD building	6.7 (-2.4)

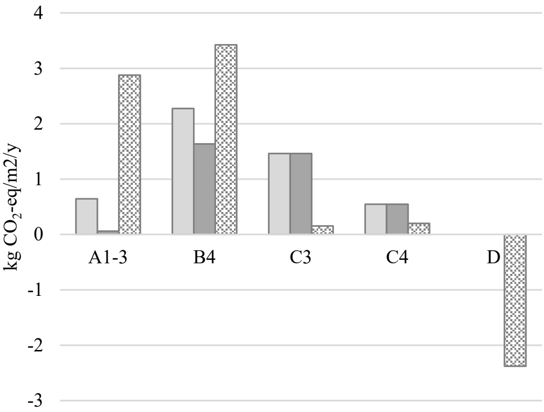


Figure 2. Impacts from the two versions of the Upcycle building (UB 0 without and UB 1 with upcycle factors) and the DfD building, distributed on life cycle stages. Note that module D is not calculated for the versions of the Upcycle building.

Figure 2 presents details of the life cycle stages in the calculated versions of the Upcycle building and the DfD building. The low impacts of the upcycled construction in the production stage A1-A3 is a combination of the low impacts from upcycled materials and the notable use of wood products with negative GWP. Replacement and incineration of wooden products, hence release of the stored carbon, result in relatively large impacts from the replacement stage (B4) and end-of-life stages (C3-C4) in both versions of the upcycle building. The DfD building causes notable emissions in production (A1-A3) and replacements (B4) compared with the Upcycle buildings. The DfD building entail potential savings in module D when (only) directly re-usable elements are assumed to have a 2nd life in a next product system as specified in Table 3. The module D potential benefits of next product system corresponds to 36 % of the impacts from the building's other life cycle stages in total.

Figure 3 presents details of the life cycle stages of the DfD building. The figure shows the time line of the construction's expected service life and the GWP 'pulses' from replacements. Furthermore, the figure shows, via the module D potentials, at which points in time DfD products are sent for reuse in other product systems, and the expected benefits these products can bring in a next system by replacing virgin-based products.

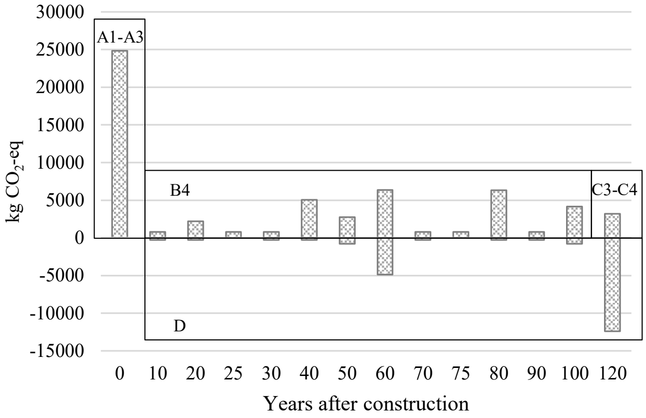


Figure 3. Details of the DfD building's life cycle stages and the GWP 'pulses' at certain points in time after the construction.

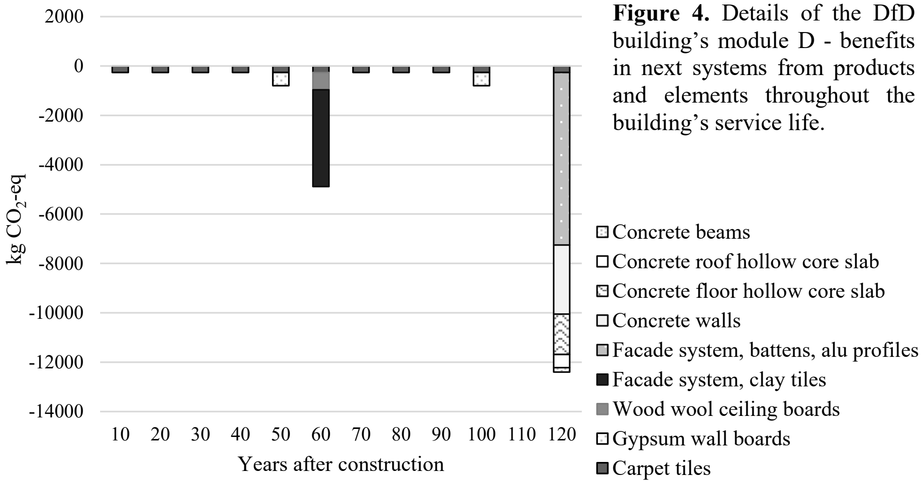


Figure 4. Details of the DfD building's module D - benefits in next systems from products and elements throughout the building's service life.

Figure 4 displays the significance of the building elements sent for direct re-use in other product systems. Apart from the decade-frequent replacement of re-usable carpet tiles, the notable pulses of benefits happen after 60 years when the ceramic tiles are reused and after 120 years when the concrete elements and aluminium profiles are reused. The concrete-based elements of the construction are contributing with 25 % and the aluminium profiles with 34 % of the DfD building's total benefits in next product systems.

4. Discussion

Amounts of insulation and windows for the DfD building are estimated, and thus subject to uncertainties regarding the inventory. Furthermore, the economic-based upcycle factors of the Upcycle building calculations is an important methodological choice in obtaining the results presented in this paper. There could be other ways of dealing with the data gap on recycled materials, which can be further explored in future research. However, even though inventory and method may affect the accuracy of results, the analysis showcase the standardized environmental assessment approach and the significance of allocation practice all the same.

Evidently, the GWP of the Upcycle building is lower than that of the DfD building. Some causes of the Upcycle building's better GWP results can be ascribed the general construction and the material choices, i.e. light frame construction with extensive use of wood-based materials (with carbon storage). However, the allocation approach of the EN 15804/15978 standards specifically promotes a system's use of recycling/reuse rather than a system providing recyclable/reusable materials by including the merits of the first strategy, but not the second strategy, to the system under study. Although module D captures the environmental benefits of the DfD strategy, it does so separated from the system's actual results, in a fashion that clearly marks the benefits as potential rather than factual, and furthermore belonging to the next system and not the system under study. The 100:0 allocation of the EN standards thus focuses on the immediate impacts rather than the impacts (potentially) happening in 120 years and encourages current low-emission design by a risk-aversive approach [15] in line with the polluter-pays principle.

The scenario-based life cycle stages, i.e. the replacements (B4), end-of-life (C3-C4) and module D are notable contributors to the GWP of both building cases. These life cycle stages are subject to uncertainties about the future processes. Hence, the prolonged time perspective of 120 years bears the likely risk that modelled scenarios will be far from reality. However, even at shorter assessment spans, the separated reporting of module D ensures a conservative approach where these speculative benefits do not 'greenwash' the overall results, but merely puts perspective on the potential after-life of the materials.

Figure 4 reveals how most contributions to module D is situated at the end-of-life of the building system in 120 years. However, recurring replacements of materials and elements throughout the service life also delivers materials for reuse, hence adding to the benefits in module D. Thus, module D's potential benefits are, in effect, relevant not only at the demolition stage of the building but also at every point in time a building product is being replaced. Only products/elements for direct reuse are considered in these calculations. However, future research on DfD in buildings could focus on shorter-lived elements of high benefit potentials. In this way it would be possible to address potentials that are not so far distanced in the future but timely relevant to promote the sustainability of the built environment.

5. Conclusions

This study quantifies the 'looping' potentials of two circular strategies applied to building design, upcycling and DfD, in the assessment practice of the European standards EN 15804/15978.

The 100:0 allocation approach of the standard means that the upcycling strategy results in lower level GWP, especially from the production stage, whereas the DfD strategy does not realize an environmental advantage within the framework of the EN standards. The standards thus represent a focus on lowering current emissions rather than crediting (potential) future emission savings to current systems.

Current analysis of module D contribution in a DfD building furthermore highlights the environmental importance of ensuring 'looping' of specific materials. Hence, the direct reuse of 800 kg installed aluminium frames in the building is the single most contributing product to the module D benefits. Thus, even though the concrete elements are notable components of the building, in weight as well as volume, developing DfD-solutions for these exact elements might not be the preferred focus for optimizing the environmental benefits provided by the building. Instead focus could be on shorter-lived elements of high benefit potentials.

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Appendix C. Publication III

Publication III: **LCA benchmarks for residential buildings in Northern Italy and Denmark – learnings from comparing two different contexts.** *Rasmussen, F; Ganassali, S; Zimmermann, R; Lavagna, M; Campioli, A; Birgisdóttir, H.* In: Building Research and Information, 2019 (47) 7 pp 833-849

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LCA benchmarks for residential buildings in Northern Italy and Denmark – learnings from comparing two different contexts

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ABSTRACT

This study provides LCA reference benchmarks for residential buildings in Northern Italy and Denmark. Furthermore, the benchmark derivation process is analysed to highlight the trade-offs that relate to the methodological choices made by benchmark developers, considering the objectives of the stakeholders. Reference benchmarks for the two contexts are calculated based on national samples of residential buildings. A comparative analysis pinpoints the methodological factors regarding system boundaries, inventory requirements and databases that, from a calculation aspect, affect the benchmarks. Results thus highlight the uniqueness of each benchmarking system put into practice, and emphasize the need for clear calculation rules and transparency within each benchmark system. The identified trade-offs from the derivation process furthermore indicate the inherent need to balance the different interests relating to the stakeholders' roles when applying the benchmark. The mapping of different trade-offs presented in this study provides benchmark stakeholders with an overview that allows for open discussion about which priorities and choices will fit a specific context of benchmark application.

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Introduction

The environmental impacts of the building and construction sector are well-known, and recent attention has shifted, not only towards the impacts from building operation, but also the embodied impacts of buildings (Birgisdóttir et al., 2017). Life cycle assessment (LCA) is the predominant method for evaluating embodied impacts, and application of LCA to the building sector has received increased academic focus in recent years (Pomponi, De Wolf, & Moncaster, 2018). Although actors in the building sector hold the potential of reducing impacts at large-scale, actual achievements are hampered because research-based method has not been implemented in industry in practice (De Wolf, Pomponi, & Moncaster, 2017). Thus, there is a need to make methods and tools more available for use with regulation bodies as well as building designers.

Towards environmental benchmarks in building design

Building designers make their design decisions by balancing a range of criteria for different aspects of performance (Marsh, 2016). These performance criteria may originate from different sources, e.g. from client or regulation, and they may be more or less measurable, e.g. quantifiable thermal transmittance or qualities of aesthetic profiling. When actively used in a design process, quantified target values concerning environmental performance have proved to reduce the environmental impacts of a building design (Russell-Smith, Lepech, Fruchter, & Littman, 2015). Benchmarking reference and target values of building constructions thus provide valuable input to the decision-making process, helping practitioners assess and improve the environmental performance of a building.

Benchmarks for building LCAs have been used for more than a decade in voluntary building certifications, such as DGNB and BREEAM, and recently there have been several examples of LCA benchmarks being considered as part of building regulations. The Netherlands was the first country to introduce a legislative requirement to measure the embodied impact of materials, although benchmarks were only later developed (Scholten & van Ewik, 2013). Currently, several countries are investigating or developing LCA benchmarks (Lützkendorf, 2017), such as France (Lasvaux et al., 2017), Sweden (Boverket, 2018) and Norway (Statsbygg, 2014).

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Internationally, the ISO 21678 standard on methodological principles for the development of benchmarks for sustainable buildings is under development as a common reference for terminology, transparency and classification of environmental benchmarks for buildings (ISO/TC 59/SC 17, 2018). Additionally, an ongoing International Energy Agency EBC Annex 72 project with over 20 participating countries is establishing harmonized methods for the development of specific environmental benchmarks for different types of buildings (Frischknecht, 2019). Several sustainability certification schemes have also developed their own benchmarks and they use these on an international level. Denmark (Mortensen, Kanafani, & Aggerholm, 2018) and Northern Italy are examples of two regions, that recognize the need to improve representativeness of benchmarks and aim to implement their own LCA benchmarks for buildings.

Challenges to harmonized benchmarks

Although parts of industry (De Wolf et al., 2017) as well as research (Gervasio & Dimova, 2018) have expressed a wish for globally harmonized LCA benchmarks, there are some obvious challenges to this. Benchmarks at whole building level change according to the variables related to the study sample analysed, such as the parameters related to the building site (Moschetti, Mazzarella, & Nord, 2015) (e.g. climatic zone, national requirements, etc.), to the construction project (e.g. function, construction systems, the building technology, etc.) (Lavagna et al., 2018; Simonen, Rodriguez, & De Wolf, 2017) and to the quality of use (e.g. occupation scenarios, technical equipment, comfort requirements, etc.).

Furthermore, benchmarks from different application contexts are also subjects to potential large-scale variations due to the LCA system boundaries, scenarios and background data included in the analysis (e.g. Dixit, Fernández-Solís, Lavy, & Culp, 2012; Minne & Crittenden, 2015). Thus, in spite of the harmonization expressed by the EN 15978 standard on LCA in buildings and construction, research shows that results from different contexts vary to the point of incomparability (Rasmussen, Malmqvist, Moncaster, Wiberg, & Birgisdottir, 2018).

These physical and methodological variations are key elements in understanding why benchmarks vary between context and why they cannot be used in a different context than the ones they were developed for (Hollberg, Lützkendorf, & Habert, 2019). This is partly due to the nature of the methodological choices taken, because each choice represents a decision and/or compromise between different alternatives. As such, it is a trade-off process and each methodological choice is made to fit the specific context. However, even though focus on benchmarks is increasing, these underlying methodological considerations have not yet been investigated in the context of benchmark derivation.

Aim of the study

This study is structured with a two-fold focus that aims to:

(1) Derive LCA benchmarks for residential buildings in Northern Italy and Denmark based on individual methods specified to the context of application
(2) Extract general recommendations for benchmark developers and benchmark holders by classifying the trade-offs and the roles in play within the different methodological considerations supporting each derivation process

Background – benchmarks in research and practice

Classifying LCA benchmarks

Every type of benchmark builds on a chosen source, as outlined in Table 1, in order to set and reach a specific environmental sustainability level for buildings. The translation from source to actual benchmarks can be based in different methods, e.g. statistical analysis of a reference sample, analysis of theoretical technical values or direct implementation of policy-related targets.

A specific division of approach can also be seen between the top-down and bottom-up benchmarks. Top-down benchmarks refer to targets set by policy, for instance the emission budget agreed at the United Nations Climate Change Conference in Paris in 2015, whereas bottom-up benchmarks are derived from a starting point in existing practice or theoretical models of ‘typical’ constructions (Häkkinen et al., 2012; Hollberg et al., 2019).

Table 1. Possible sources for different types of benchmarks. Adapted from Lützkendorf, Kohler, König, and Balouktsi (2012).

Benchmark type	Possible source for values
Target value	National/government targets
	Technical optimum
	Financial optimum
Best practice value	Best practice
	Statistical analysis of data (Upper quartile)
Reference value	Statistical analysis of data (Median)
Limit value	Legal minimum
	Prescriptive minimum

Research literature presents some examples of benchmark setting from a top-down target value approach (see Table 1), aiming to identify the target that should be reached for an environmentally sustainable building design (Brejnrod, Kalbar, Petersen, & Birkved, 2017; Zimmermann, Althaus, & Haas, 2005). However, most available literature on benchmarks presents bottom-up derived reference values based on statistical analyses of samples of real buildings (De Fátima Castro, Mateus, Serôdio, & Bragança, 2015; Ji et al., 2016; Lasvaux et al., 2017; Rasmussen & Birgisdóttir, 2019; Simonen et al., 2017) or of 'typical' buildings (König & De Cristofaro, 2012; Lavagna et al., 2018; Moschetti et al., 2015; Wittstock, Löwe, Fischer, Braune, & Kreißig, 2010). A recent study by Hollberg et al. (2019) proposes a method for combining bottom-up reference values of building components with top-down benchmarks per capita for the building as a whole.

Trade-offs and stakeholders in LCA benchmarking practice

The Oxford English Dictionary defines a trade-off as 'a compromise between two desirable but mutually exclusive features'. In LCA, trade-off frequently refers to the situation in which one solution performs better in a specific impact category (e.g. global warming potential) than another solution, but worse than the other solution when changing focus to a different impact category (e.g. acidification potential) (see e.g. Hertwich & Hammitt, 2001). This implies a focus on weighing results, whereas the trade-offs that are relevant in the application of LCA, and thus relevant to this study, relate to the fundamental set-up of the LCA study itself.

As benchmarks are often tailored for use in a certification system (Hollberg et al., 2019), the defined method of the benchmark is subject to application by industrial practice, e.g. building designers. Implicitly, this type of industrial application requires the balancing of being easy enough to perform and still providing reliable outputs (Ny, MacDonald, Broman, Yamamoto, & Robèrt, 2006; Peace et al., 2018), hence there is a trade-off between the method's accuracy and its ease of application.

Another aspect related to accuracy concerns the need for representative data to build the model. This is indeed a well-known issue when it comes to technological, geographical and temporal representativeness of inventory or impact assessment data (JRC, 2010; Lasvaux, Habert, Peuportier, & Chevalier, 2015), and guidelines exist on how to select generic data on construction products (Silvestre, Lasvaux, Hodková, De Brito, & Pinheiro, 2015). The trade-off thus entails balancing a high level of representativeness with the given availability of data and information.

A trade-off is furthermore apparent in presenting results on the basis of m^2 and year of reference study period. In this way, emissions occurring at modelled replacement after 80 years of service life contribute equally to the results as the emissions happening at the construction site today. Lützkendorf, Lorenz, and Michl (2017) argue that the future events should be considered as 'risks' (of emissions, etc.) and relate this to the method of discounted cash flows. This approach highlights focus on the more certain events in relation to production and construction. Choosing reference study period is thus a balancing act between acknowledging the long technical service life of buildings and taking into account the inherent uncertainty of the scenarios for the use stage.

A multitude of stakeholders can be involved in the benchmarking process, each having their interests form part of the methodological considerations and trade-offs. Häkkinen et al. (2012) group a long list of stakeholders in sustainability assessment methods into four types of roles in the process: (1) the role that orders the assessment, (2) the role that provides information for the assessment, (3) the role that elaborates the assessment and (4) the role that uses the assessment results. This grouping does not necessarily cover all application aspects, but it emphasizes the fact that one stakeholder can have more than one role in the process.

The two application contexts

In Italy, there are no LCA-based benchmarks for buildings, nor is there much incentive to use LCA. In rare cases, practitioners apply LCA and compare the results with the LCA benchmarks set in the international 'green building' rating systems, although these are not calibrated for the Italian construction context. Such benchmarks are related to a specific rating system and set through different benchmarking methodologies, LCA system boundaries and impact categories (Ganassali, Lavagna, & Campioli, 2016, 2017). In this way, it is not feasible for Italian practitioners to compare the LCA benchmarks of different rating systems and their level of sustainability. The LEED certification contains the only benchmarking that Italian practitioners can apply at the early design stage, modelling a reference building against which to compare the environmental improvement of the building design, i.e. on a case-by-case approach. The North Italian context is founded in this lack of regional LCA benchmarks and aims at defining a replicable benchmarking approach for new residential buildings.

In Denmark, the practice of building LCAs originated from a national database and tool development, the BEAT (Building Environmental Assessment Tool) model, used around 2000. In 2012, an adapted version of the DGNB certification scheme, which includes a building LCA, was introduced. Political awareness was raised in 2014 by a governmental strategy for the built environment pointing to the use of LCA to ensure environmentally efficient buildings (The Danish Government, 2014). In parallel, the national building authorities had a new tool, LCAbyg, developed to make building LCA accessible to building designers, owners and investors (Birgisdottir & Rasmussen, 2019). Recent political focus has centred on developing a voluntary, sustainability building code as part of the building regulations (The Danish Government, 2018). LCA will form part of the environmental evaluation, and further development of LCA benchmarks will thus contribute with a scale for assessing a building's environmental performance.

Materials and methods

This study of benchmarks and their corresponding methodological considerations is based on cases of North Italian and Danish residential buildings that were available in detail to the authors of this paper. The authors operate in these regional contexts, and the authors' involvement in benchmark derivation qualifies them for first-hand insight into the contextual decisions that shaped the benchmarks. In both regional contexts, the derivation of benchmarks for residential buildings is highly relevant, due to the inclusion in certification schemes and, in the Danish case, potential inclusion in the building regulations.

LCA-based benchmarks for both contexts were set through statistical analysis of LCA outcomes of the sample, defining an evaluation scale with three sustainability levels: the median, reflecting the conventional construction practice (reference value), the first quartile, for the best practice values and the third quartile, for the limit values.

Study samples

Table 2 synthesizes information and the building features of the residential buildings contained in the Italian and Danish reference samples for the benchmarking processes. The detailed characteristics about the individual buildings are presented in the supplemental material.

Table 2. Overview of building types and details on the residential building cases.

	Italian sample	Danish sample
Number of buildings	28 buildings	7 buildings
Type of residential building	3× Single-family houses	4× Terraced houses
	25× Multi-family buildings	3× Multi-family buildings
Specific use	Family housing	Youth housing (1 building)
		Assisted living facility (3 buildings)
		Family housing (3 buildings)
Building project/ client	Private clients	Social housing organizations and public authorities
Reference unit	Impact potential/ (m^2 * year)	Impact potential/(m^2 * year)
	m^2 is based on gross heated floor area	m^2 is based on gross floor area
Climate zone	zone E (2100-3000 HDD)	2906 HDD
	zone F (more than 3000 HDD)	
Construction period	2015–2017	2014–2018

The Italian study sample consists of 28 residential buildings (single-family and multi-family buildings) constructed between 2015 and 2017 and certified with the Italian energy scheme CasaClima Nature (CasaClima, 2017). The buildings' energy performance, i.e. envelopes and constructive systems, is standard for the period of construction, and with transmittance values in accordance with the Italian energy standard for buildings (D.Lgs 141/2016; D.Lgs 311/2006; DPR 59/2009). The use of heating and cooling systems is related to the climatic zones and is in compliance with the Italian regulation (DPR 142/1993) about the management of building heating and cooling systems.

The Danish case sample consists of seven residential buildings (multi-family and terraced houses) that were constructed between 2014 and 2018. The buildings are all certified with the Danish version of the DGNB certification system for residential buildings (Danish Green Building Council, 2016). The energy performance of the buildings complies with legislative requirements on maximum allowed use of operational energy in new buildings (BEK, 1615/2017).

LCA procedures

The LCA procedures for each national analysis follow European standard EN15978 on sustainability of construction works (CEN, 2012). Total amounts of construction materials and energy demands for the Italian life cycle inventories were provided by CasaClima Agency. The building information relayed by CasaClima Agency concerns the construction materials, the calculated annual demand of energy (heating and electricity

Table 3. Italian and Danish LCA methods and modelling details.

	IT	DK
Reference study period	100 years (IBO/CasaClima database)	120 years (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013)
Production of construction materials (A1-3)	Inventory data provided by the CasaClima Agency	Inventory data provided by the Danish Green Building Council
Assumptions for transportation in construction (A4)	Transport by lorry for distance of 50 km for inert material and 300 km for additional materials (Wittstock et al., 2010)	Not included
Assumptions for construction (A5)	Accounts for 2% of production phase impacts (Asdrubali, Baldassarri, & Fthenakis, 2013; Scheuer, Keoleian, & Reppe, 2003)	Not included
Replacement scenario (B4)	Service life of building elements from (IBO database)	Service life of building elements from Aagaard et al. (2013)
	No replacements if the expected service life of the replaced building element exceeds the remaining service life of the building by 2/3. No replacements the last 10 years of a building's service life (Aagaard et al., 2013)	
Energy use in operation (B6)	Includes heating, cooling*, ventilation, hot water supply, lighting. On-site production of energy is subtracted from the total energy requirement. (However, negative energy use is not possible).	
	Static energy scenario based on Italian grid mix from Ecoinvent.	Dynamic energy scenario with increased use of renewable energy 2015–2050 (COWI consulting, 2016)
Water use in operation (B7)	Potable water consumption of bathrooms, kitchens and irrigation system.	Not included
Assumptions for transportation in EoL (C2)	Transport by lorry for distance of 20 km for inert and non-hazardous waste and 250 km for hazardous waste (Wittstock et al., 2010)	Not included
Assumptions for waste processing and disposal (C3–C4)	Landfill for inert: concrete based products, plaster and mortar, bricks, stones, ceramics and glazing Landfill: plasterboards, fibreboards, mineral wool panels, wood fibre panels, glue and rubber products and synthetic insulations Incineration: wood, plastic insulation panels. Recycling: metals (Blengini, 2009; Italian waste regulations)	Landfill for inert: aerated concrete and mineral wool, glazing Waste processing for recycling: concrete and bricks, plasterboard Incineration: wood, plastics and bituminous sheets Recycling: Metals
Use of standards and methods	Following the calculation rules of standards ISO 14040–44 and EN15978 and characterization methods: • CML-IA baseline – version 3.4 (for Global Warming Potential and Acidification Potential) • Cumulative Energy Demand (CED) – version 1.09 (for renewable Primary Energy and non-renewable Primary Energy)	Following the calculation rules of standards ISO 14040–44 and EN15978 as applied in Danish adaptation of DGNB International • CML-IA baseline – version 4.1. • Primary energy use, renewable total (from EN 15804 as implemented in Ökobaudat) • Primary energy use, non-renewable total (from EN 15804 as implemented in Ökobaudat)
Use of databases	EcoInvent 3.3	GEN_DK (an extract of the Ökobau 2016 LCIA database)
Modelling tool	Excel	LCAbyg 3.2 (Birgisdottir & Rasmussen, 2019)

*The Danish case buildings do not have cooling installed

for building operational energy use) and water, plus the production of renewable energy from photovoltaics (where present). In the Danish sample, the amounts of building materials were provided by the DGNB certification documentation. The DGNB documentation also provided the mandatory energy calculations for operational energy use, specifying how much heating and electricity is supplied from grid or on-site installations. Table 3 presents the LCA method and modelling details for the Italian and the Danish contexts.

Table 4 illustrates the life cycle stages covered, while Table 5 illustrates the building parts included in the inventory. The Italian inventory only includes building parts related to the thermal envelope, i.e. what is required by CasaClima certification for the energy calculation. In the Danish inventory, more building parts are included, e.g. main aggregates of the technical systems such as PV panels or ventilation system.

In this paper, the LCA benchmarks used for the comparison analysis are focused on three impact categories, namely Global Warming Potential (GWP), Acidification Potential (AP) and Total use of Primary Energy (PEtot). As a group of indicators, the three impact categories have proved to represent the breadth of 7 impact categories that are used in typical Danish building LCAs (Marsh, 2016).

Mapping methodological considerations

The choices made within each case of benchmarking derivation are mapped in the declaration framework of

Table 4. Life cycle stages covered (as defined in EN 15978).

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

Table 5. List of buildings parts included in the Italian and Danish LCA inventories (based on EN 15978).

	Foundation, structural frame and non-load bearing elements										Technical systems									External works				
	Foundations	Frame (beams, columns, slabs)	External walls	Doors	Staircases, ramps, balconies	Internal walls	Windows	Roof	Floor	Ceiling	Sanitary systems (water, waste water, piping, pump and fixed equipment)	Heating and hot water systems	Drainage system	water treatment systems	Fixed fire-fighting systems	Communication and security systems	Transportation inside the building (lifts, escalators)	Mechanical ventilation and air conditioning	Fixed lighting systems	The site construction	Landscaping	On-site drainage	External lighting	External parking
IT		x[a]	x		x[b]	x[c]	x	x	x	x														
DK	x	x	x	x	x	x	x	x	x	x	x[d]	x[d]						x[d]						

[a] Only slabs.
[b] Only loggias.
[c] Only between heated and unheated spaces.
[d] Only main aggregates.

the current draft version of the standard on Methodological principles for the development of benchmarks for sustainable buildings (ISO/TC 59/SC 17, 2018). The draft standard lists information requirements of three types: (A) Basic information, (B) System boundaries and methods and (C) Source and type of information. Each type contains a number of subset information details. In a regular application, the declaration framework will be used to present the information details, i.e. the methodological choices, of benchmark derivations as presented in Tables 2 and 3. In this study, the declaration framework is used to highlight the considerations that applied to the choices made in the two contexts under study. The considerations are then linked to the general trade-offs outlined in the Background section. The mapping thus highlights the extent to which specific methodological concepts are balanced in the practical derivation of benchmarks.

Based on Häkkinen et al.'s (2012) classification of stakeholders into the role they play, three roles are identified as prevalent in the benchmarking context of Northern Italy and Denmark: (1) The role that orders the assessment and defines the overall goal, i.e. the benchmark holder, who could be represented by e.g. a certification system. (2) The role that provides information and elaborates the benchmark system, i.e. the benchmark developer, who could be LCA professionals in academia or practice. And (3) the role that uses the defined method to assess own projects in relation to the benchmarks, i.e. the benchmark user, who could be represented by building design engineers or architects.

Results

North Italian and Danish LCA benchmarks

Table 6 presents the statistically derived benchmarks of North Italian and Danish samples. Table 7 further presents the relative contribution of LCA stages in Italian and Danish LCA results for GWP, AP and PEtot. North Italian reference values of three impact categories (GWP, AP and PEtot) show how the impacts related to the operational stage (with energy performance and climate zones as specified in the Study Samples section) are higher than the embodied impacts of materials. This is related to electricity and heating impacts, which are often based on natural gas. 72% of overall GWP and PEtot and about 66% of total AP are related to operational energy demands. The embodied impacts of materials (i.e. all impacts related to Production, Construction, Replacements and End-of-life, see Table 4) have a relative contribution of between 24% and 31% of the life cycle impact potentials. The Danish sample presents the opposite trend: the embodied impacts contribute with 75%, 70% and 64% of the GWP, AP and PEtot life cycle impact potentials, respectively, while the operational phase contributes with 25–36% of the life cycle impact potentials.

Figure 1 illustrates the variability in results of GWP for the life cycle stages included in the North Italian and Danish benchmarking approaches. Italian and Danish Replacement results show how module B4 can have the same relative contribution of the Product stage in the overall embodied impacts; sometimes, the Replacement share is even higher than the Product stage share, according to the impact category analysed. The additional LCA stages in the Italian benchmarking approach does not influence the final benchmarks of embodied impacts notably: the Construction process stage (modules A4–A5) has a relative contribution of 1% of the overall impacts, while Transport of materials (module C2) towards disposal has a relative contribution of around 0.15%.

The operational impacts are notably higher for all three impact categories in the Italian cases than in the Danish ones. This reflects the different energy scenario employed, which is static in the Italian benchmarking and dynamic in the Danish scenario, i.e. employing a policy-based, projected energy supply of low-fossil electricity and district heating. Furthermore, the Italian variability of operational impacts is notable compared with the variability of the Danish results. The difference is mainly related to the technical solutions applied in the buildings and to the overall energy demand of the buildings. The Italian cases thus span the use of natural gas boilers, heat pumps and district heating whereas only district heating examples are found in the Danish samples. The total energy demand (electricity and heating) of the Italian buildings falls between 30 and 50 kWh/m^2/y, compared to Danish buildings with energy demands in the range of 4–40 kWh/m^2/y. These expected energy demands also reflect the use of different energy standards in the two regions.

In the overall operational impacts of the Italian scenario, the consumption of fresh water (module B7), modelled as specified in Table 3, has a relative contribution of between 3% and 4%.

Contributions related to life cycle inventory

In addition to the choice of LCA system boundaries, the inclusion of different building parts in the Life Cycle Inventory (e.g. exterior walls, slabs, etc.) can affect the LCA outcomes and the benchmark values. Figure 2 presents the variability of GWP impact results of the North Italian and Danish building samples, in which different building components are included in the inventory.

Table 6. Reference LCA benchmarks of North Italian and Danish residential buildings*. Median values of samples**.

	Italian Benchmarks			Danish Benchmarks		
Impact	**Total**	**Embodied**	**Operational**	**Total**	**Embodied**	**Operational**
GWP kg CO_2-eq/m^2/y	13.8	3.80	10.4	8.2	6.00	2.17
AP kg SO_2-eq/m^2/y	0.0656	0.0189	0.0455	0.0227	0.0181	0.00827
PEtot MJ/m^2/y	279	62.7	207	132	85.1	53.9

*The different system boundaries and LCA modelling specified in Tables 5 and 3.

**Note that the median values are derived from three different parts of the results: the Embodied, the Operational and the Total. Hence, the Total median is not the exact sum of Embodied median and Operational median.

Table 7. Relative contribution of LCA stages* to the total median of the North Italian and Danish LCA results**.

	A1-3		A4-5		B4		B6		B7		C2		C3-4	
Impacts	**IT**	**DK**	**IT**	**DK**	**IT**	**DK**	**IT**	**DK**	**IT**	**DK**	**IT**	**DK**	**IT**	**DK**
GWP $kgCO_2eq/m^2/y$	12%	23%	0.92%	–	10%	40%	72%	25%	3.7%	–	0.17%	–	1.6%	12%
AP $kgSO_2eq/m^2/y$	11%	34%	1.10%	–	15%	35%	66%	30%	3.3%	–	0.12%	–	3.2%	1.4%
PEtot MJ/m^2/y	12%	30%	0.72%	–	12%	37%	72%	36%	3.0%	–	0.15%	–	0.7%	−2.3%

*Note the different system boundaries and LCA modelling specified in Tables 5 and 3.

**Note that relative contributions may not add to 100% due to rounding of numbers.

In the Italian sample, the External wall and Windows categories have the highest variability. High GWP impacts are related to these two categories, which are followed by Roof and Deck and Slabs. External wall and Windows have high GWP values due to the presence of materials with high GWP impacts in the production stage (e.g. concrete, bricks and aluminium) and high replacement rates (e.g. glazing and frames of windows with an expected service life of 35 years). Stairs, etc., and Interior walls present low GWP values because of the limited number of elements in the sample: in Stairs, etc., only external floors of loggias are accounted in the inventory, while Interior wall category includes only the interior walls between heated and unheated spaces (see Table 5). This is related to the CasaClima energy certification requirement, which includes the thermal

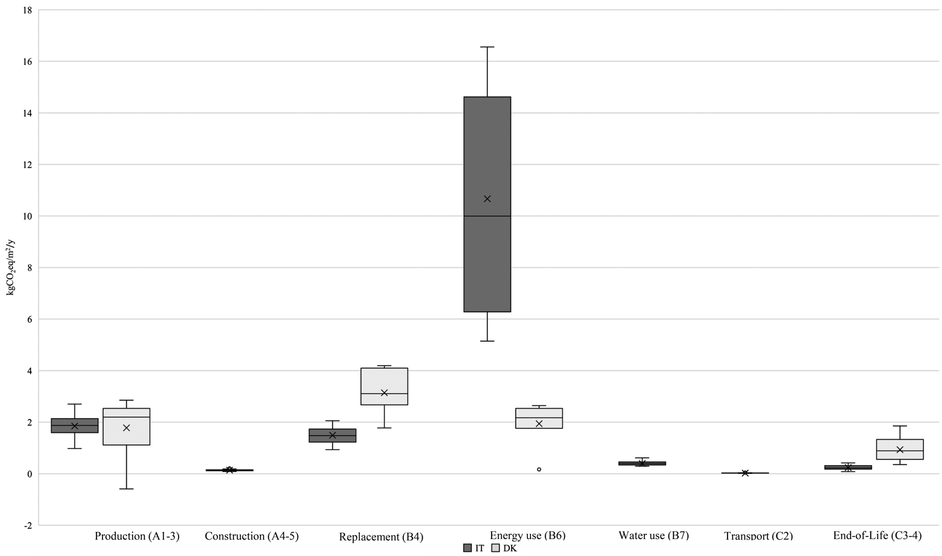

Figure 1. Statistical variability of North Italian and Danish GWP impacts for all life cycle stages included in the benchmarking methods.

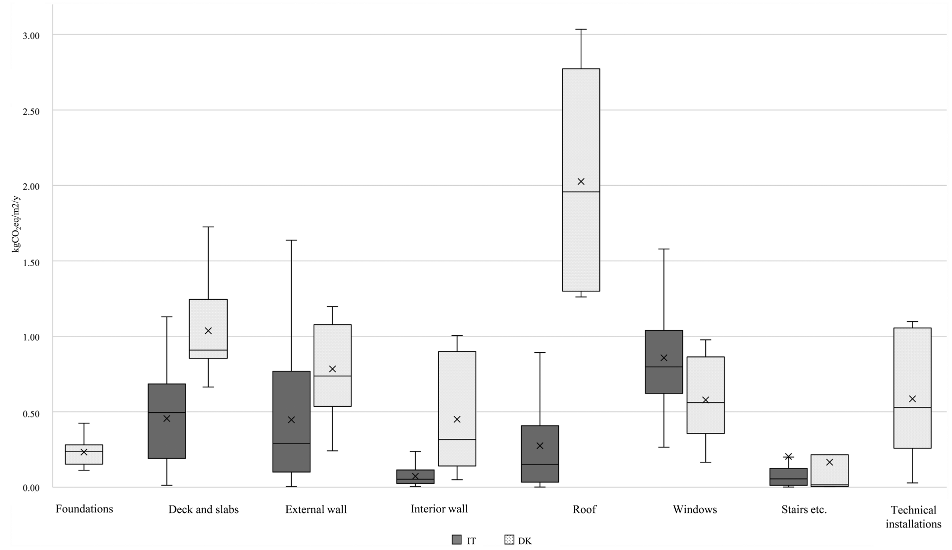

Figure 2. Statistical variability for North Italian and Danish embodied GWP from different building elements.

envelope of building in the energy calculation, excluding balconies, stairs and floors/walls between heated spaces.

The Danish sample has the highest GWP values and variability in the Roof category, because of the common use of bituminous roofing felts with frequent replacement cycles. High GWP impacts are seen in Deck and Slabs and Exterior wall. However, Technical installations also constitute up to 14% of the total embodied impacts in some of the cases. The AP and PEtot variability of Italian and Danish benchmarking approaches are illustrated in the supplemental material.

The analysis of different inventories shows how the inclusion of different building parts in the life cycle inventory can affect the LCA outcomes and the benchmarking results of different construction contexts. The differences not only lie in the component categories involved in the LCA analysis (e.g. Foundations and Technical installations), but also in the specific building parts included in the categories. Indeed, the floors included in Deck and Slabs and the walls counted in Interior wall are different between the two national samples, because of the different level of inventory comprehensiveness within the two certification systems.

Influence of background data

A comparison between seven key building materials from the two databases applied is shown in Figure 3(a–c), in absolute values and in the relative deviation between Ökobau and Ecoinvent. Table 8 reports the data name chosen from each database to represent the production stage (A1–A3), the waste treatment and disposal (C3–C4) and the required service life (RSL) of materials in the two approaches. Full details about the data names are in the supplemental material. Figure 3 (a–c) shows large variations within specific materials, and different patterns between the three impact categories. Hence, the notable GWP deviation of 80% between bitumen sheet data relates to the incineration scenario applied for the Danish approach. In AP, the deviations are generally high; between 50–70% for concrete, glazing bricks and bitumen sheet. For the plasterboard, the data set values differ by a factor 2. In the PEtot category, the construction wood numbers are notably higher from Ecoinvent than from Ökobau. The notable difference in emission trends of the construction wood is further treated in the discussion section.

Trade-offs in the benchmark derivation

Table 9 illustrates the trade-offs identified from the considerations that formed part of the North Italian and Danish benchmark approaches (see the specific choices of the approaches in Tables 2 and 3). The considerations represent a balancing of concepts, i.e. trade-offs between features. In more than half of the choices made for the two benchmark approaches, the considerations are the same for both regional approaches. However, this does not mean that the actual method is the same in both cases. For instance, in both cases, the temporal validity

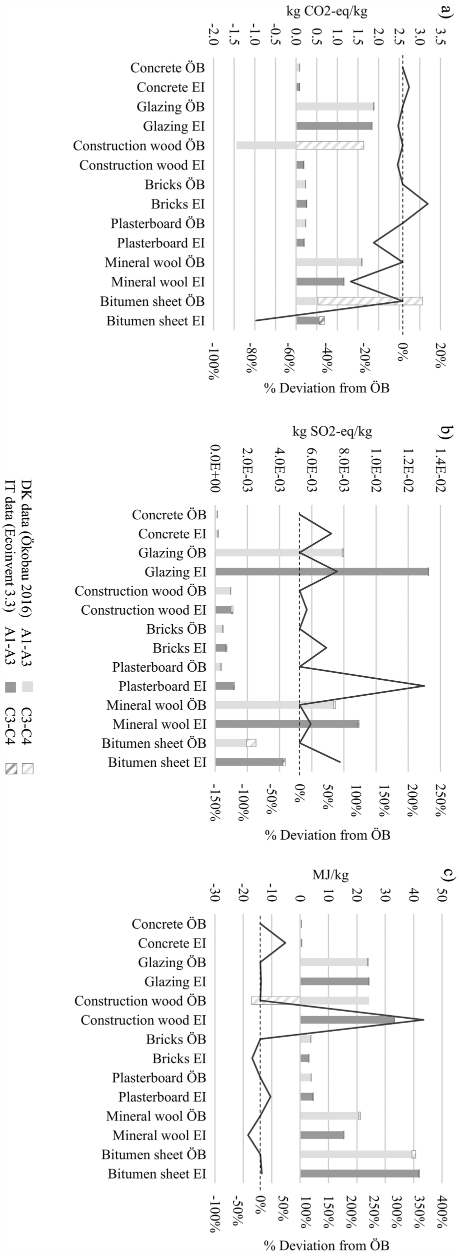

Figure 3. (a–c) Impacts from selected construction materials from the Ökobau database, abbreviated ÖB, and the Ecoinvent database 3.3, abbreviated EI. The line graphs show the deviation in percentages relative to the Ökobaudat impacts.

of the benchmarks (A06) is given from their respective available sample, but these two different samples of building cases are clearly very different, being from different construction contexts.

As a main methodological choice, the specific type of benchmarks (A02) for limit, reference and target values is, in both approaches, set from a bottom-up perspective, relative to the average performance of current buildings. This choice is in contrast to the alternative top-down concept of setting the targets in relation to a definition of absolute sustainability. The choice is, in its essence, a fundamental choice related to the goal of the benchmarking system, and thus pertains to the benchmark holders field of action.

A larger number of the subsequent modelling choices are related to the trade-off between obtaining sufficient representability of data and scenarios, and between using the data and scenarios that are available to benchmark developers as well as users. For instance, the representability of the Danish sample is challenged by a small number of just seven building cases (C02). Nevertheless, the limited number of cases was all that was available at the time of assessment. Additionally, both regional approaches use the classification type 'residential buildings' for the benchmarks (A03), although this is a generic term for the varying subtypes of cases that were actually available in the samples, i.e. mixtures of stand-alone housing units, terraced houses and multi-family houses. Assumptions for the different modules (B05–B07) are also based on available, current scenarios, although the preconditions for these assumptions change with time, e.g. via regulation.

The representability of the background database is also balanced against the pragmatic approach of using the available data. In the Danish context, database accessibility and maintenance were part of the considerations and the choice was therefore to connect to the German database Ökobau, although the geographical representability as well as the transparency was inhibited with this choice.

Both approaches apply the technical service life of buildings for the RSP (B01) and for the conversion to reference units (impact per m^2/year) (A05). This technical, deterministic approach takes into account the full life cycle of the durable building materials, but contrasts with the view, presented in the Background section, of the long use stage as incorporating inherent uncertainties.

The building inventory (B02) and the scope of life cycle stages (B03) are in both approaches determined in a fashion that balances the ease of application for

Table 8. Overview of key construction materials from the DK (Ökobau database 2016) and IT (Ecoinvent database 3.3) approach, their required service life (RSL) and the data naming from the respective databases.

Material		RSL	Product stage (A1–A3) data	Waste treatment and disposal (C3–C4) data
Concrete	DK	120	Concrete_25_30	Waste treatment (crushing)
	IT	100	Concrete, high exacting requirements, cement CEM II/A	Waste concrete, inert material landfill
Glazing	DK	25	Thermal glazing 2-layers	Inert material landfill
	IT	35	Glazing, double, $U < 1.1$ W/m^2 K	Waste glass, inert material landfill
Construction wood	DK	120	Construction wood	Construction wood incineration
	IT	100	Sawnwood, softwood, raw, dried ($u = 10\%$)	Waste building wood, municipal incineration with fly ash extraction
Bricks	DK	120	Clay tiles	Waste treatment (crushing)
	IT	100	Clay brick	Inert waste, sanitary landfill
Plasterboard	DK	40	Gypsum plaster board (impregnated)	Waste treatment (crushing)
	IT	50	Gypsum plasterboard	Inert waste treatment of inert waste, sanitary landfill
Mineral wool	DK	50–80	Mineral wool	Construction waste, landfill
	IT	50	Stone wool	Inert waste, sanitary landfill
Bitumen sheet	DK	20	Bitumen sheet G 200 S4	End of life – incineration of plastic based materials
	IT	25	Bitumen seal, V60	Waste bitumen, sanitary landfill

benchmark users against the accuracy of the benchmark and subsequent assessments. Additionally, in the studied cases, there is an interaction between the theme of representability versus availability and the theme of accuracy versus ease of application. This is visible in the choice of inventory scope (B02), where the starting point for the derivation is the sample available to the benchmark developer. In both the North Italian and the Danish case, the sample does not cover the full inventory (see Table 5), i.e. it is not fully representative to the buildings. This selective scope is then implemented in the benchmark calculation rules to ensure the ease of practical application for benchmark users, even though the selective scope will compromise the accuracy of the final results to some degree.

The final type of trade-off identified from the comparison of the two regional approaches is method consistency versus methods integration. This refers to the pragmatic need to adapt and combine existing methods as opposed to following one method fully. In both approaches, the methods integration is apparent. First, for both, in an overall fashion (B09) by having adapted the standardized method EN 15978, for instance to only include selected parts of the life cycle. Second, for the Danish modelling of operational impacts (B08), a dynamic forecasting of the operational emissions is undertaken, although the embodied emissions are modelled in a conventional, static way. Third, in both approaches, the applied benchmarks for operational impacts (B04) are not set from the LCA calculations made as part of the derivation. Rather, the integration of existing regulation via the Energy Performance in Buildings Directive (EPBD) was applied in the implemented benchmarks. However, the dynamic modelling of operational impacts was kept in the Danish approach, as described in Rasmussen and Birgisdóttir (2019). Again, the considerations leading to methods integrations can be seen as overlapping with the benchmarks user's perspective of having a benchmark system that is easy to apply in practice by integrating existing regulation, e.g. regarding energy performance.

Discussion

Factors of influence to benchmark results

Some general trends related to the differing methodological approaches can be observed by comparing the numerical results of the North Italian and Danish benchmarks. First, the percentage contributions from embodied and operational impacts are approximately reverse between the two approaches. This indicates the notable influence of the methodological differences, in particular the Danish dynamic modelling, in which energy mixes for district heating and electricity use (module B6) are modelled based on forecasts, reflecting the expected grid changes toward more renewable-based energy. The potential influence of future energy mixes to building LCA results is highlighted in existing literature (Collinge, Landis, Jones, Schaefer, & Bilec, 2013; Li, Zhu, & Zhang, 2010), although this approach has not previously been applied within a benchmark system.

The applied databases showed a high level of discrepancy in impact potentials from selected materials in Figure 3(a–c). Naturally, the choice of a specific dataset to represent a specific material is a source of uncertainty in this comparison. However, the comparison of GWP related to bitumen sheets also highlights the influence

Table 9. Benchmark methodological choices, the related considerations of the North Italian and Danish approach and the trade-offs that these considerations represent.

Benchmark information		**Considerations in benchmark approach**	
		Northern Italy	***Denmark***
Basic information, type			
A02	Type of benchmark	Defining sustainability relative to the current average performance of buildings	
A03	Type of building	Available sample used	
A04	Description of the type and pattern of use, service life and necessary issues to define the functional equivalent		
A05	Information about reference units	Reference unit chosen as results per m2 per year of RSP to facilitate horisontal comparisons in a common unit similar to the reference unit used in energy certifications	
A06	Temporal validity of the benchmark	Available sample used	
A07	Geographical validity of the benchmark		
System boundaries and methods			
B01	Reference Study Period	Chosen as the expected technical service life of the building itself to take into account the full life cycle of the durable building components	
B02	Building elements covered (inventory)	Includes what is already known to designers from the thermal energy calculations	Requires additional estimations/measurements of material use than what is already known from mandatory thermal energy calculations
B03	Life cycle stages covered	Including more life cycle stages based on generic background data, e.g. construction	Selection of the life cycle stages assumed to affect results most notably
B04	Energy use in operation	Even though LCA results are calculated for B6, the operational benchmarks are set based on what is already in existing regulation	
B05	Assumptions for module A	Based on what is in the existing, regional certification system and/or practice, e.g. regarding scenarios for replacements and waste treatment of materials	
B06	Assumptions for module B		
B07	Assumptions for module C		
B08	Other assumptions	-	Dynamic energy scenario towards a low carbon grid is applied for environmental data for operational energy (B6) to ensure that the impact of materials are not underestimated in a conservative, static approach to energy scenario modelling
B09	Use of standards/methods	Striving for compliancy with international and European standards, but modifying for reasons of simplicity, e.g. number of impact categories	
B10	Use of databases	Ecoinvent - Prioritising transparency for the benchmark developers	Ökobau - Prioritising accessible database based on previous experience with challenges in running own database
Source and type of information			
C01	Description of source of information	Available sample used	
C02	Number of buildings		
C03	Age of building related data		
C04	Type of information		

Trade offs

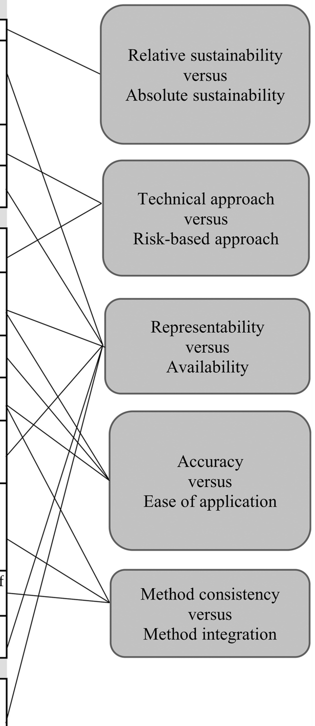

Table 10. Influence on embodied GWP results of changing the reference study period of the building from the originally set RSP (shaded).

	GWP (kg CO_2-eq/m^2/years)			
	IT		DK	
RSP: 50 years	5.40	+40%	7.86	+31%
RSP:100 years	3.86	100%	5.98	−0.3%
RSP: 120 years	5.25	+36%	6.00	100%

of different assumptions between the scenarios applied for different contexts, in this case an incineration scenario for the Danish waste treatment and a landfilling scenario for the North Italian scenario. Figure 3(a) furthermore points to the notable difference of the two databases in the ways stored carbon is either included in the data (Ökobau) or not included (Ecoinvent). The stored carbon in the Ökobau shows as a negative emission in the production stage and a positive emission in the waste treatment, i.e. incineration. Likewise in Figure 3 (c), the differing methods of calculating primary energy use, non-renewable as well as renewable (described in Frischknecht, Wyss, Knöpfel, & Stolz, 2015), generate the notable difference between databases for the construction wood. This simple comparison of frequently used materials highlights how the databases vary, and why it is important that benchmark users apply the same database by which the benchmarks are developed.

Figure 1 illustrates how replacement of materials in the life cycle of a building adds considerably to the total embodied benchmarks, especially in the Danish case. The combined effect of materials' service lives (as exemplified in Table 8) and the reference study period (RSP) is of great importance to the benchmarks showcased in this study. The replacements gain additional significance from the long RSP of 120 years and display the potential effect on results from the scenarios and assumptions applied for the operational stage. Lasvaux et al. (2017) showed how a prolongation of RSP from 50 to 100 years reduced the GWP/m^2/year of residential benchmarks by 18%. The reduction was explained by the increased number of years on which to distribute the impacts from durable building elements. Table 10 illustrates the influence of GWP benchmark results through the change of RSP of the buildings in the Danish and North Italian samples of the current study. As seen from Table 10, the reference values change rather unpredictably between RSP's of 100 and 120 years. This reflects the service life of materials in the models and points to the fact that both national systems rely on service life tables in which some large-scale replacements (of e.g. insulation) are effectuated around year 100. The analysis thus shows that a linear relationship between RSP and impacts cannot be expected, due to the service life tables being tailored to the specific assessment system and predetermined RSP.

The choice of RSP is only treated to a limited extent in existing research and without clear indications on the most optimal way of setting this parameter. Although it is recognized that RSP influences the results when converting to reference units (see e.g. Aktas & Bilec, 2012; Grant & Ries, 2013), the core challenge of harmonizing the approach to RSP is in the value-laden perspectives of the RSP choice. A long RSP may take into account the durability of the components of the building, but it introduces a notably higher level of uncertainty regarding the use stage scenarios, for instance of products' lifetime (Aktas & Bilec, 2012). However, by extending the RSP to more than 50–60 years, the environmental burdens of a building project exceed the choices made within one adult generation. From this follows that the use of long RSPs for calculations and conversion to reference units essentially puts emission burdens on future generations by passing on constructions affixed an embodied emission load of 6 kg CO_2–eq/m^2/year (in the average Danish case, see Table 6). This is notwithstanding the fact that a notable part of these emissions actually took place in the very first year of the study period, i.e. at the time the building materials were produced (Säynäjoki, Heinonen, & Junnila, 2012). Hence, multiple considerations about timing, responsibility and uncertainties are needed when determining the reference study period used in a benchmark system.

Trade-off mapping and classification

The identified trade-offs illustrate how the decisions taken by specific stakeholder roles in the application context are not black and white choices between one or the other option, but scalable compromises between ideal solutions and the pragmatic reality of the applied LCA.

The mapping of trade-offs in this study is performed within the generic trade-offs identified mainly on the basis of literature although one additional trade-off about Method consistency versus Methods integration proved relevant in the current case. However, the mapping is necessarily performed in an interpretive fashion which leaves room for other interpretations about which decisions are connected to which trade-offs.

The definition of stakeholder roles is representative to the current cases whereas other roles and their connections to the specific trade-offs may be identified differently if the same analysis was executed in another context. Additionally, the different roles may form part of the same stakeholder, e.g. the benchmark holder that also has the role of developing the benchmark.

Limitations of samples

A general limitation of the current study lies in the fact that only two approaches where compared and analysed for the underlying trade-offs. Furthermore, both approaches calculate bottom-up reference values based on limited samples of case studies. Hence, if a larger and more diverse set of benchmark approaches were evaluated, additional types of trade-offs may be encountered as playing a role in the derivation process.

Within each of the investigated benchmark derivations, a limited sample size is also prevalent. The benchmark values are only as accurate as the limited set of inventories used to calculate them, which makes the inventory samples potential sources of uncertainty. This is partly due to amounts of building materials being reported from third parties, which means that structure and content of data may vary. Additionally, the sheer sample size of the Danish buildings in particular is small.

The limited sample sizes furthermore challenge the representability of the type of building that the benchmarks are defined for, i.e. the generic term ‘residential buildings’. Moschetti et al. (2015) showed that there were noteworthy differences between the benchmarks from, e.g. single-family houses and apartment blocks.

Therefore, the benchmarks should preferably be recalculated when more building cases are available to ensure improved accuracy and representability of results.

Conclusions

This study provides LCA benchmarks for residential buildings in Northern Italy and Denmark and makes use of the derivation process to highlight the trade-offs that form part of the considerations made by benchmark developers, taking into account the associated roles and interests in the benchmark system.

The results of the benchmark derivation provide the North Italian and the Danish building sector with bottom-up reference values for current building practice. A comparison of the two approaches furthermore shows that the numerical values of the two benchmark approaches vary considerably and that these variations can be explained by the different ways of modelling operational energy, as well as the different life cycle stages, inventory scope and databases used in the benchmarking systems. The most obvious difference between the two benchmark approaches is the method used for calculating impacts from the operational energy. The North Italian approach applies static emission factors for the energy, whereas the Danish approach applies emission factors that reflect future low-carbon energy grids. This makes the operational impacts (from energy and water demand) account for approximately 69—76% and embodied impacts account for 24–31% of the total life cycle impacts in the North Italian approach, whereas the numbers are reversed in the Danish approach. A database comparison of the datasets used to calculate impacts from materials furthermore shows that background data varies profoundly for specific materials, and that it is important that benchmark users apply the same database by which the benchmarks were developed.

The benchmark results thus highlight the uniqueness of each benchmarking system put into practice, and they confirm the existing literature that cautions against horizontal application of benchmarks. This implies that when a benchmark system is based on a certain database and certain assumptions, these methodological choices must become the ‘rules’ for users, otherwise the results are, in effect, not comparable with the benchmark. A high level of detailed rules on method as well as transparency is needed to make studies comparable within the same benchmarking system.

In addition to the numerical benchmarks, this study expands the current body of benchmark literature by classifying the decisions made in the benchmark derivation and relating these decisions to the underlying trade-offs in the North Italian and Danish cases. The trade-offs indicate the inherent need to balance opposite interests and responsibilities that relate to the stakeholders’ roles in the benchmark application. The benchmark holder’s role is apparent in defining the overall goal of the benchmark scheme, i.e. determining whether the scheme applies a bottom-up perspective relating to current building practice or whether the scheme applies a top-down approach relating to a more absolute definition of sustainable buildings. A notable part of the methodological decisions taken concerns the role of the benchmark developer and balancing the use of available information (e.g. data) versus ensuring well-founded representability of results. Lastly, considerations of the user’s role are mainly apparent in the methodological choices that concern the ease of application versus the accuracy of results.

Further development of the North Italian and Danish benchmarks could incorporate the top-down perspective to better reflect on the absolute sustainability of the sectors. Additionally, the benchmarks as well as the trade-off identification are vulnerable to the limited sample sizes. Thus, further work could consolidate the findings of this study by enlarging the sample size for derivation as well as for the trade-off analysis.

Overall, the study provides the two specific contexts of Northern Italy and Denmark with a set of benchmarks that can be applied in the construction sectors to improve the relative environmental performance of buildings. Furthermore, the mapping of different trade-offs presented in this study can provide benchmark stakeholders with an overview that allows for an open discussion about which priorities and choices will fit a specific context of benchmark application.

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Appendix D. Publication IV

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Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings

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ABSTRACT

The importance of embodied energy and embodied greenhouse gas emissions (EEG) from buildings is gaining increased interest within building sector initiatives and on a regulatory level. In spite of recent harmonisation efforts, reported results of EEG from building case studies display large variations in numerical results due to variations in the chosen indicators, data sources and both temporal and physical boundaries. The aim of this paper is to add value to existing EEG research knowledge by systematically explaining and analysing the methodological implications of the quantitative results obtained, thus providing a framework for reinterpretation and more effective comparison. The collection of over 80 international case studies developed within the International Energy Agency's EBC Annex 57 research programme is used as the quantitative foundation to present a comprehensive analysis of the multiple interacting methodological parameters. The analysis of methodological parameters is structured by the stepwise methodological choices made in the building EEG assessment practice. Each of six assessment process steps involves one or more methodological choices relevant to the EEG results, and the combination potentials between these many parameters signifies a multitude of ways in which the outcome of EEG studies are affected.

1. Introduction

Buildings are responsible for more than 40 percent of global energy used, and as much as one third of global greenhouse gas emissions [1]. The environmental impacts from buildings are of operational as well as embodied character, where embodied energy and greenhouse gas emissions (EEG) from buildings concern exchanges with the environment from processes that take place in relation to the life cycle of the building materials, for example the production processes of cement clinker which requires heating energy and which emits CO2 from energy conversion as well as chemical processes. It is increasingly recognized that EEG can constitute more than half of the total life cycle impacts from new buildings and is thus a key element to address when working towards a more sustainable building sector [2].

On a regulatory level, focus from international, as well as, from regional political bodies may act as a driver for national development of measures to reduce EEG from buildings [1,3]. Preliminary steps towards regulatory guidelines and/or requirements are thus seen in several countries [4–7]. This regulatory attention follows an already existing focus within the building sector itself, where voluntary initiatives include EEG considerations as part of holistic evaluations of the sustainability of buildings, e.g. as practiced in various certification schemes.

Furthermore, methodological improvements have been made in developing and harmonising the life cycle assessment (LCA) method by which the EEG is quantified. Building and construction related standards include the international standard ISO 21931-1:2010, which specifies the framework for methods of assessment of the environmental performance of construction works, and the European standard EN 15978:2011 which specifies a calculation method for assessing the environmental performance of a building. In parallel with the standardisation development, a number of international research projects have focused on LCA and EEG in

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Table 1
Summary of Annex 57 case study properties for case studies analysed in this paper.

Total number of case studies	59
Study origin (country)	Austria (AT), Switzerland (CH), Germany (DE), Denmark (DK), Italy (IT), Japan (JP), South Korea (KR), Norway (NO), Sweden (SE), United Kingdom (UK)
Number of databases employed	19
Range in applied reference study period (RSP)	20–150
Number of applied system boundary combinations	18
Building types	Office, residential, school

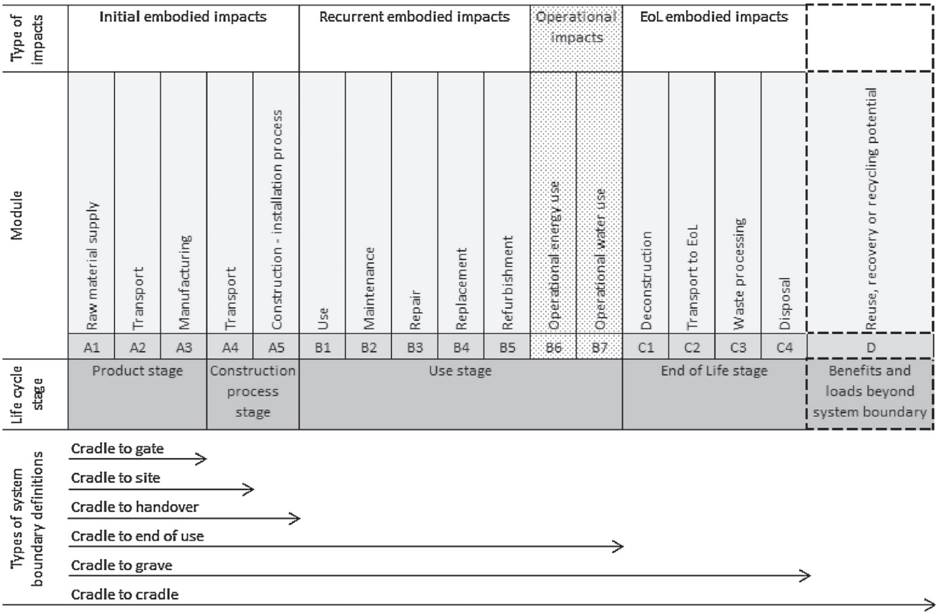

Fig. 1. System boundaries definitions in relation to the life cycle stages of a building [30,29,18].

the building sector. These activities are carried out e.g. in a European context [8–10], but also in an international context through e.g. the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC). Relevant IEA-EBC research work include, most recently, the Annex 57 on EEG in buildings (2011–2016) [11].

In spite of all the attention towards EEG and the efforts in harmonising a methodological approach, research has pointed to the lack of consistency in the ways building LCAs are carried out, both in terms of system boundary definition and in terms of the indicators and the background data used for calculating the embodied impacts [12–15]. Thus, reported EEG of buildings display large variations in numerical results as well as inconsistent and insufficient reporting formats [16].

Knowledge on how to reduce EEG through certain design strategies can be drawn from the experiences and analyses of the, so far, mostly individual case studies. This can guide building designers, as well as, policy developers targeting reductions of EEG. However, it is highly important that the methodological reasons for differences in EEG results is fully understood. Conversely, incorrect conclusions may be drawn and used for creating and validating EEG-reducing design strategies, although these may not actually have the desired reduction potential. Existing literature, mainly in reviews, has described methodological parameters of importance, further explained in Section 1.2. However, the parameters treated in existing literature appear randomly sought out and thus do not provide a systematic overview that links directly to the EEG assessment practice.

The aim of this paper is to add value to existing EEG research knowledge by systematically explaining and analysing the methodological implications on the quantitative results obtained, thus providing a framework for reinterpretation, more effective comparison and understanding of reduction potentials in quantitative terms.

The systematic approach of this paper includes the consideration of the already scientifically addressed methodological parameters, which are presented in the literature review in Section 1.2. The method Section 2 introduces a structured framework for analysis based on the practical assessment process of the EN 15978 standard. Furthermore, Section 2 describes the collection of over 80 building case studies from the IEA-EBC Annex 57 project, an international collection of EEG assessments that are reported in a consistent and organised manner and thus provides detailed and illustrative examples of methodological implications. The results and discussion Section 3 uses the quantitative as well as the qualitative properties of the Annex 57 case studies to analyse and empirically validate the methodological parameters that affect the outcome of EEG studies, and the section presents a comprehensive and structured overview of these.

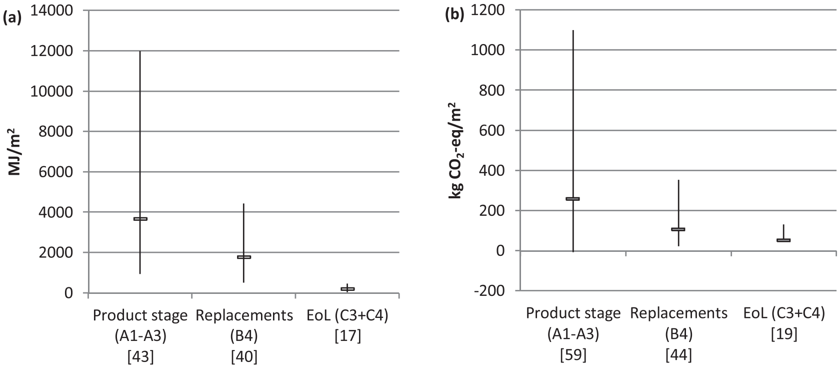

Fig. 2. EE (a) and EG (b) averages and ranges from selected reported life cycle stages. Square brackets indicate number of case studies included in the displayed ranges.

1.1. Defining the concept of EEG

Life cycle environmental impacts from and resource uses in buildings are often categorised as being operational or embodied. Operational energy is intuitively understood and defined as being the energy needed to maintain comfortable conditions in the building through processes such as heating, ventilation, air conditioning, hot water supply, lighting or operational waste management [17–19]. The emissions of energy-related pollutants from the building operation, e.g. greenhouse gasses such as CO_2, can likewise be regarded as operational impacts [20]. In contrast to the impacts related to operational energy use, embodied energy use and greenhouse gas emissions are understood as material-related impacts, i.e. the impacts stemming from the processes that take place in relation to the life cycle of the building materials [21,2,22].

EEG may be sub-classified to reflect the part of the building life cycle in which they occur. Typically, this way of classifying embodied impacts is divided into initial and recurring embodied impacts. Initial impacts signify those related to the processes occurring up to the point in time where the building is taken into use, and recurring impacts signify the material-related processes occurring throughout the building's use stage, e.g. maintenance and replacements [17,2]. Added to the initial and recurring embodied impacts are the impacts which occur after the end of the building's service life. These are commonly termed demolition impacts [23,17,2], although they also cover waste treatment, transport and disposal processes as well as impacts from the demolition processes. Some studies suggest the benefits and loads from recycling potentials as an additional life cycle stage of importance to the life cycle impacts of a building [24–26]. The integration of this life cycle stage as an element of the embodied impacts however, depends on the modelling approaches towards recycling used in the life cycle inventory of a particular study [27,28]. Consequently, results from this life cycle stage are recommended or required as reported separately from the results of the remaining life cycle stages [26,29,30].

EEG studies of buildings display wide variations in terms of the life cycle stages included [31,32]. It can thus be useful to distinguish between different types of system boundaries used in studies of EEG in buildings, for instance by a cradle to gate perspective where impacts are accounted from processes only to the point in time where the building materials are ready to leave the gate of the manufacturing facilities. The EN 15978 standard, published in 2012, presents a modular structure for defining five main life cycle stages; production, construction, use, end of life (EoL), and finally the benefits and loads beyond the system boundary. This modular structure can be further categorised to reflect impacts at the different types of system boundary definitions as illustrated in Fig. 1.

1.2. Ranges of and sources for EEG variations

1.2.1. Variations of EEG results

Embodied energy use of buildings is mainly addressed in literature within the context of life cycle energy evaluations, hence including the operational energy use in the building's use stage. A review by Sartori and Hestnes [33] thus found the embodied energy's share to range between 2 and 46% of the total life cycle energy. Ramesh et al. [17] reviewed many of the same case studies as well as newer studies and found a numerical range of embodied energy use between 7 and 143 kWh/m^2/year. Reviews focusing on the initial embodied energy use of buildings reports numbers in ranges between 1500 and 19,400 MJ/m^2 [34,21,35,36]. Hence, horizontal comparisons of EE studies show ranges spanning up to an approximate factor 20.

Studies reporting ranges of EG in buildings are fewer than EE studies, but still expresses variations in the reported ranges of results, i.e. in Hammond and Jones [21] and Hacker et al. [37] where the initial EG is reported to vary between 228 and 606 kg CO_2-eq/m^2, hence an almost three-fold difference.

As indicated from these previous reviews, the variations in results of EE and EG are profound. Part of the variations can be explained by variations in building design, materials used, building function, etc., that is, physical properties of the buildings, their location and use. One example is the study by Passer et al. [38] comparing variations of building material solutions for a single family house presents ranges of 4.5–7 CO_2-eq/m^2/year and 17–25 kWh/m^2/year for the initial embodied impacts. These results are within a range with maximum variations of approximately 70% or a factor of 0.7 and thus only explains part of the 20- and three-fold differences. Ramesh et al. [17] review results distributed on building types and show practically the same large variations within the categories of offices and residential buildings, 30–140 kWh/m^2/year and 7–143 kWh/m^2/year respectively, hence pointing to building type as an inferior determinant of the results when comparing different studies.

Thus, differences in building designs may account for some of the variations of EE and EG results presented in literature, but the better part of the variations seem determined by the study design i.e. the methodological choices made for the assessment. Sources for these variations are randomly described in various literature sources which mainly focus on the indicator definitions, the background data, the modelling approach, the system boundaries and

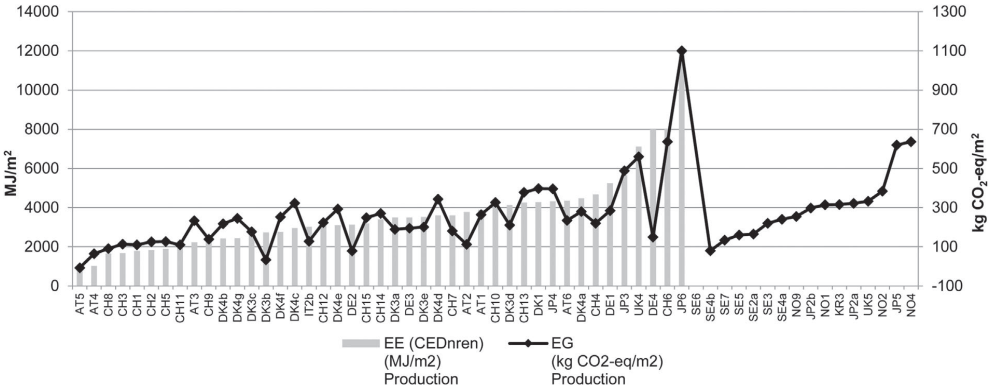

Fig. 3. EE and EG of product stage (module A1–A3) of the Annex 57 building case studies.

the scenario definitions [18,12,39,2,17,40], which are all explained in more detail in the following Sections 1.2.2–1.2.6.

1.2.2. Definitions of EE and EG indicators

Embodied energy (EE) is most appropriately accounted for in its primary form, i.e. at the energy source level before conversion, as opposed to the end-use energy at consumer [33,18]. The indicator used to express the primary energy use (PE) is also referred to as cumulative energy demand (CED), a term that expresses the accumulative nature of the indicator in which energy uses from different processes of the life cycle stage are successively added. However, as described by Frischknecht et al. [41], there is no harmonised definition of the indicator. Hence, the reported use of primary energy in a study may rely on choices of upper or lower heating values in chemical energy resources, the energy content in uranium and the determination of energy resource inputs of renewable energies. Furthermore, the feedstock energy, e.g. the retained energy in petrochemical-based plastics and rubbers, is rarely reported as being included or excluded of the primary energy indicator of building case studies [29,18,42].

There is also a range of varying definitions and considerations for the embodied greenhouse gas emissions (EG). EG is closely related to energy since fossil or bio-based energy generation releases the greenhouse gas (GHG) CO_2, and thus the CO_2 emissions related to energy use are proportional for a given fuel mix [2]. However, there are two main aspects which mean that EG is not directly proportional to EE. Firstly, EG includes CO_2 as well as other greenhouse gasses, although the actual types of included greenhouse gasses may differ according to the chosen scope which can be e.g. the GHGs from the Kyoto protocol or the GHGs from the latest IPCC report. Fluorocarbon gasses as regulated by the Montreal Protocol may also be included [43]. In relation to defining the types of GHGs are also the considerations on the characterisation factors used to express all included GHGs in CO_2-equivalents and the temporal scope in which the emissions and environmental loads are considered [13].

Secondly, EG also includes emissions of greenhouse gasses from chemical and physical processes during the life cycle of the building materials, e.g. CO_2 from the cement clinker process or leakage of fluorocarbon gasses from air condition appliances [13]. Correspondingly, building materials of biological origin, e.g. wood products, may sequester and temporarily store CO_2. There are different approaches for accounting for biogenic carbon storage in LCA, and these can lead to large differences in the final EG results [44,45].

1.2.3. Representativeness of background data

Representativeness of background data concerns the fundamental match between the processes included in the building model and the background data which describes the environmental impacts of the process. The ISO 14044:2006 data quality requirements addresses the importance of representative data at three levels of coverage; time-related, geographical and technological coverage [46]. In relation to EEG, these aspects are also identified as contributing to the difference in results found in several studies of applied building LCA [12], in the comparison of different generic databases [47,40] and in the comparisons of generic databases and environmental product declarations (EPDs) [48–50].However, clarification and harmonisation is still needed, for example on aspects of system boundaries, allocation practices and service life of products and buildings [51].

1.2.4. Modelling approaches

Two distinct modelling approaches are used in LCA practice; the input-output based and the process based. Hybrid models based on the two are also used. The two approaches possess different strengths and limitations in terms of completeness and accuracy [15,18]. These are reflected in reported EEG results where input-output and hybrid based models tend to produce results in higher ranges [52].

1.2.5. System boundaries

The difference in chosen system boundaries is pinpointed in several review studies as one of the foremost reasons for incomparability between EEG studies of buildings [18,32,17,31]. A progressive development towards a harmonised approach in reporting the building's life cycle stages has taken place following the international and European standardisation efforts in this field. However, the aspect of system boundaries is not limited to clarifying the building's life cycle stages. Dixit et al. [39] describes how the system boundaries may in reality be characterised as consisting of three distinct dimensions that are all spanning upstream and downstream processes;

1. One dimension covers the life cycle stages, e.g. extraction of raw materials or transport of materials to building site. Some research highlights the need for simplification of the included life cycle stages in order to limit the amount of calculation work and thus to make the LCA and EEG evaluations implemented and used by architects and engineers as part of the building design process [10] [53,54]. Other research points to the relevance of some life cycle stages that are often omitted from

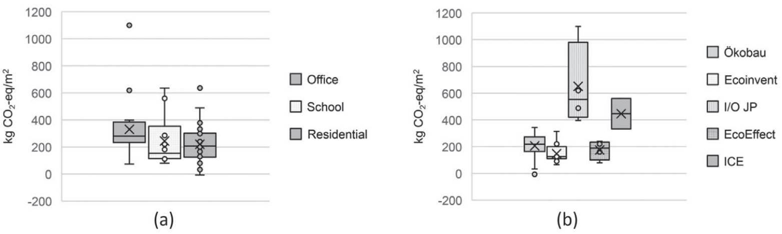

Fig. 4. a–b. Boxplots illustrating the distribution of EEG results from cases based on reported characteristics for building use type (4a) and database applied (4b).

studies, e.g. the construction stage, or the transport to site [55,56] and emphasises the additional relevance by the timing of GHG emissions from the before-use stages [57]. Naturally, the difference in included life cycle stages leads to difference in EEG results. However, as noted by for instance Optis et al. [16], the simplifications of life cycle stages follow the goal and scope of the study in question.

2. A second dimension covers the width of included inputs and outputs for each life cycle stage, e.g. the resources used as input for the extraction of raw materials. This affects results at two levels; at inventory level for building/building component, where e.g. omitting fixtures and fittings in some cases may be significant [56]. Secondly, at inventory level for materials found in the applied building material databases, where there may be differences in the number of substances and emissions accounted for [58].
3. A third dimension that covers the physical entity being assessed, e.g. building component level or building with site. Because this dimension indicates the scope of the study, this naturally changes across different studies.

1.2.6. *Scenario definitions*

Scenario related differences found in literature focus on building level scenarios as well as material level scenarios. For building level scenarios, studies have stressed the influence on EEG results of the building's estimated service life, which in turn influences the total amount of materials used for replacements etc. Aktas and Bilec [59] refer a range of LCA studies in which the building service lives are explicitly stated as being arbitrarily set, hence underlining the lack of a viable method to estimate a building's life time. Several building case studies have investigated predetermined sets of potential service lives in order to address the sensitivity of the modelled results [60,61] or specifically focusing on the impact on results of service life variations [62,63]. Some studies also present methodologies for addressing the combined effects of variations in the building's service life and variations in the service life of materials [59,64].

Apart from the service life aspect, scenario analyses on building scale furthermore include approaches to evaluating the significance of scenarios for single life cycle stages, e.g. scenarios for construction [65,66]. At building material level, investigations of scenario choices include those of maintenance frequencies [67], transport [68] and EoL treatment options [25,69,70].

2. Method

2.1. *The Annex 57 case study collection*

The IEA-EBC Annex 57 research work was organised into four subtasks, each focused on different aspects of EEG in buildings [11]. Subtask 4 was responsible for identifying strategies for the reduction of EEG. In order to do so, the subtask 4 work group collected more than 80 building case studies from the multi-national project partners, chosen to be representative of the information on EEG currently available both in emerging academic publications and within different national contexts [71].

The purpose of the Annex 57 case study collection was to produce a body of different detailed studies, carried out in different countries and for different purposes, for which the relevant data was easily accessible and identifiable. The case studies were subjected to four sequential analytical perspectives: the impacts of methodological issues on the EEG results obtained (the focus of this paper); comparing the impacts from different life cycle stages, materials and components; evaluating design and construction strategies which can be used to reduce EEG from buildings; and considering the influence of geo-political, organisational and cultural context on the measurement and reduction of EEG [72].

The initial preparatory work was the development of a systematic template, designed to allow the widest variety of studies – including qualitative studies – whilst encouraging transparency and completeness of quantitative data [73]. This approach enabled the comparable interpretation of the high number of complex and detailed case studies by multiple authors. Case studies were submitted using the prepared template, and raw data or public academic literature and reports were also made available and were referenced within each case study description. The case studies as transcribed to the templates therefore all report a number of specific characteristics in a consistent manner; the databases used for calculations, the reference study period, the included life cycle stages of the assessment (based on the modular framework of the EN 15978 standard) and the building type and location.

In spite of the template format, reported EEG results of the case study buildings were still given in a wide variation of formats, for example from the total EG over the full building life cycle per m^2 floor area per year (kg CO_2-eq/m^2/year), to only the EG from the building materials production stage (cradle to gate). For further use in the analysis, these diversely reported results have been adjusted for the reported floor area, reference study period and reported life cycle stages.

The case study collection spans a wide range of EEG case studies carried out for different purposes and is valuable in the sense that it also includes examples of how building LCA is applied in practice. Hence, the studies are not only aimed for international research and scientific publications but also contain evaluations of EEG carried out as part of certification schemes, national research projects and academic theses.

2.2. *A structure for identification of significant parameters*

In order to identify and discuss the parameters causing varying EEG results in a structured manner, the analysis of the Annex 57 case studies is based on the EN 15978 standard and the assessment process defined therein (further specified in Table 2 of Section 3.3). In contrast to the more general LCA guidance of the ISO 14040–14044 and the ISO 21931-1, the EN 15978 focuses on a specific approach to set up a study and calculate the potential impacts.

In this sense, the standard reflects the assessor's practice and it covers the step-wise methodological choices that require attention in the assessment procedure [30]:

- Identify purpose of assessment
- Specification of the object of assessment
- Scenarios for the building life cycle
- Quantification of the building and its life cycle
- Selection of environmental data and other information
- Calculation of the environmental indicators

Additional, final process steps of the EN 15978 approach; "Reporting and communication" as well as "Verification" have been left out of this analysis as they do not specifically address the assessor's choices regarding methodological choices in the study.

3. Results and discussion

3.1. Reported EEG results from Annex 57 case studies

The EEG results of the Annex 57 case studies are displayed in this section in order to obtain an overview of the quantitative background results used for the analysis and discussion of methodological parameters. This background overview includes displaying the varying ranges in results as well as the numbered case studies which are later referred to in Section 3.2 as part of the analysis. Table 1 presents a summary of the properties of the case study collection. Appendix A provides further details of the specific case studies and their individual properties in terms of country of origin, the building type, databases used for calculations, the reference study period, and the included life cycle stages of the assessment. Further qualitative details of the case studies are specified in the case study collection report [71]. In the following analyses, specific case studies are referred to by country and case study number, e.g. AT3.

Fig. 2a–b presents the ranges of and average EE and EG of selected life cycle stages reported as part of the Annex 57 case study template. EE expresses the cases where results were explicitly reported as being non-renewable primary energy use, i.e. CEDnren. The numbers represent new construction as well as refurbishment projects, further detailed on case study level in Appendix A. Refurbishment cases report numbers for all, in the refurbishment, installed materials as part of the product life cycle stages (modules A1-A3–refer Fig. 1).

The numbers showcased in Fig. 2a–b are specified for impacts within the same system boundaries (refer Fig. 1) of either product stage (A1–A3), replacements during the use stage (B4) or selected EoL processes (C3 + C4). As shown in Fig. 2a–b, the ranges span profoundly, especially for the product stage EE and EG. Reported numbers of EG range between −7 and 1100 kg CO_2-eq/m^2 and reported numbers of EE range between 943 and 12,000 MJ/m^2. Note here, that the negative EG-result (−7 kg CO2-eq/m2) reflect methodological implications of the inclusion of temporal carbon storage in wood. This is further discussed in Section 3.2.5.

When adjusting results for the reference study periods used, the 41 case studies reporting product and replacement stages range the total EG between 0.3 and 18.2 kg CO_2-eq/m^2/year, i.e. a 60-fold difference. The 40 case studies reporting product and replacement stages for EE, show a range in the embodied impact of these life cycle stages between 16 and 210 MJ/m^2/year, i.e. an almost 15-fold difference.

Fig. 3 displays EE and EG of the product life cycle stages, modules A1-A3, for each case study building (refer Fig. 1). Results are ordered by increasing EE and the corresponding EG, although EG results reported without EE are also displayed in the right-hand side of the graph. Fig. 3 shows how an increase in EE seems to be followed by an increase in EG. A linear correlation analysis between the two variables EG and EE yields an R^2-value of 0.70 signifying that there is a relationship between the two indicators. However, the relationship is not straight-forward because it reflects the multitude of underlying methodological parameters across the studies.

The differences in EEG results can further be specified according to some of the reported characteristics of each study. Fig. 4a shows the EG results from the production stage (A1–A3) sorted by building use and 4b shows the EG results sorted by five of the applied databases.

Fig. 4a–b shows two ways of categorising the results due to study characteristics. The figure also highlights how some characteristics are more influent than other, in this example it shows that results grouped by building use type reveals a variation in results although when grouped by database the variations become even more apparent. Each of the two characterisation types are only indicators of the specific case parameters affected; for the use type, this includes differences in building layout and material inventory etc. For the database type, this includes differences in GWP definitions, representativeness of data etc.

3.2. Significant methodological parameters of Annex 57 studies

In the following, the Annex 57 case studies are analysed and discussed within the framework of the assessment process steps outlined in Section 2.2.

3.2.1. Identification of the purpose of assessment

The Annex 57 case studies present a range of different purposes for the individual studies. Examples include evaluations of early stage design decisions (SE2a, SE2b and SE5), assessments for different certification or benchmarking purposes (AT studies, DK4, CH studies), comparison of design options (UK5) and profiling for comparison with operational impacts (NO studies). The purpose of assessment, consisting of a defined goal and stated intended use, is the first step of an LCA study according to the international ISO 14040-series as well as the EN 15978 standards. These different stated purposes hence lead to variations in the subsequent methodological choices about functional unit, scope and other parameters made in each study. Standardisation is suggested as a general approach to limiting the uncertainties caused by choices in an LCA study [74]. However, as exemplified in the Annex 57 case study collection, the stated purposes of the building EEG assessments vary broadly and cause a wide range of diversity in the reported studies and results. Hence, a methodological one-solution-fits-all seems possible only on a theoretical scale although a highly detailed level of standardisation may be appropriate within certain contexts of purpose, e.g. for national certification, regulatory purposes or building-level EPDs.

3.2.2. Specification of the object of assessment

The Annex 57 case studies reflect a variation of different building types spanning various sorts of offices, residential single- or multi-family houses, schools and retirement homes. Even though the building type may point to some functional requirements of the building, this does not give any indications about the choice of building designs (e.g. high-rise concrete structure or single-storey wooden construction) nor the technical properties (e.g. thermal performance) that are relevant for embodied as well as operational impacts. Technical requirements such as thermal performance of the building is directly connected with not only operational impacts but also embodied impacts caused by material use in order to attain the required performance. However, reported performances such as "low-operational energy building" or "zero-emission building" as seen in the case studies, may still be perceived differently on an international scale due to differences in definitions and due to the different climatic conditions under which the buildings operate. The multitude of descriptions in the Annex 57 case studies of functional equivalents and physical characteristics of buildings points to the challenges in describing core functional and technical requirements as well as physical properties in a uniform and consistent way and thus complicates the possibilities of comparing studies horizontally.

An additional aspect of the functional equivalent is the reporting of results per m^2 floor area, a declared unit often used in conjunction with the functional equivalent. Even though individual studies may specify whether usable floor area or gross floor area is the reference unit, these terms may cover slightly different definitions from country to country. For instance, the heated floor area is in Norway measured to the inside of the external walls but in Denmark this is measured to the outside of the external walls [75]. Furthermore, national practices may vary as for how to include m^2 from parts of the building that are non-conditioned, e.g. basement or terraces.

The reference study period (RSP) is an important factor for the calculation and reporting of EEG results due to the relative significance of the recurrent embodied impacts. In the Annex 57 case studies, the reported RSPs range from 20 to 150 years and thus present very different perspectives on the temporal aspect of the assessment. The choice of RSP can be viewed from two perspectives; firstly as a numerical exercise for calculating annualised impacts, an often preferred way to report results of a building LCA. Reported annualised performance of a building can thus be much misleading depending on the context, for instance if only the cradle to gate EEGs are included in the assessment. The second perspective of the RSP is as a parameter reflecting the actual design, where solutions for extension or limitation of the building's service life are sought after. This latter perspective is employed in some Annex 57 case studies displaying examples of embodied impacts from increasing earth quake resistance performance to obtain an increased service life of building (JP4, JP6) or by adapting the building design to protect weaker components, such as windows, in order to increase the service life of these (DK3a-b).

As already thoroughly explored in literature, the significance of system boundary definitions to the EEG results cannot be understated. Standards and scientific recommendations suggests full inclusion of all life cycle stage processes, or transparency and clear descriptions about potential system boundary simplifications (such as cradle to gate) [30,13]. However, the Annex 57 case studies show how EEG assessments in practice operate with selections of process modules across life cycle stages. Only in few examples do the case studies follow the recommended system boundary types such as cradle to gate (SE studies) or cradle to site (NO4). The reasons for this disparity between recommendations/standards and practice may on the one hand be explained by the relatively recent harmonisation of approach. On the other hand the disparity may also reflect how the defined goal and intended use of the studies vary from study to study. In this sense, the varying system boundary definitions may each suit their specific purpose and hence question the very usefulness of a general harmonisation of EEG studies.

3.2.3. *Scenarios for the building life cycle*

Scenario definitions and the influence on the EEG results are explored from different angles in some of the Annex 57 case studies, sometimes as part of the goal and other times as part of sensitivity analyses. Case study (JP7) thus explores different scenarios for the EoL treatment of a wooden house as part of the goal of the study. Case study (DK1) is an example of a case study evaluating the scenario of the building's service life as part of sensitivity analyses.

The relatively long service life of a building implies special attention towards the use stage scenarios that are relevant to the EEG, in particular the scenarios that describe how materials, components or the building itself is maintained, repaired, replaced and refurbished. The underlying factors determining the impact on EEG results of these scenarios can be narrowed down to the *scale* of intervention and the *frequency* of intervention. Replacement of building materials is the most frequently included use stage process in the Annex 57 studies. A detailed account on the actual assumptions and scenarios for all replaced materials is not present in any of the case studies, which is to be expected due to the large amount of documentation work this would require. Some studies refer to national guidelines on the replacement frequencies (e.g. DK, DE and AT studies). However even within one country, assessment practice may be influenced by various sources for material service life definitions, e.g. by scientific research centres and specific product manufacturers, thus resulting in significant variations of scenarios applied for comparable buildings and modelling [72].

Other relevant scenario choices highlighted in some Annex 57 case studies relate to the EoL processes assumed to take place after the building's end service life. For specific constructions, some EoL processes and benefits from next product system may prove to significantly influence EEG results, e.g. in a wooden structured high-rise building (UK9) evaluating the effect of using a scenario of direct reuse of the wood (assumed the standard scenario) or a scenario of incineration without heat recovery.

3.2.4. *Quantification of the building and its life cycle*

The quantification of the building and its life cycle is, in the assessment practice showcased by the Annex 57 case studies, a matter of inventory level of detail and source of data. The access to a high level of detail for the specific building is based on knowledge that is progressively developed alongside the development of the building project itself. How this higher or lower level of detail may affect the EEG results can be evaluated in some of the Annex 57 case studies where the as-build highly detailed inventory (NO4) contributes to EG results that are notably higher than a comparable building case calculated at the very preliminary design stages (NO1)[72]. The early design stage evaluations may prompt relevant inventory simplifications and cut-off practices and hence result in lower calculated EG results as exemplified in some cradle to gate and early design stage evaluations (see SE2b, SE4).

3.2.5. *Selection of environmental data and other information*

The differences between and the need for harmonisation of methodology in EEG database sources are thoroughly discussed in scientific literature. Thus, within each building material database lies a range of inherent methodological choices, e.g. of data representativeness and system boundaries. The Annex 57 case studies report the usage of 19 different databases. Furthermore, 30% of the case studies report using two or more different data sources in the assessments. The choice of database for an assessment may rely on factors such as availability or apparent geographical representativeness without further considerations on other specific details of importance to the calculated EEG results, e.g. whether the database considers carbon storage in wood products. However, this exact modelling detail of carbon storage seem imperative to the relatively low cradle to gate EG results reported in some studies (AT2, AT5, DK3b, DE2, DE4). When not balanced properly by EoL processes' release of the stored CO_2, the results of a cradle to gate assessment can turn negative (AT5) or simply just generate EG results in the lower range (e.g. DK, DE and AT studies) compared with studies using other databases. Hence, when these EG numbers are used outside context, in simplified system boundaries representations, and without sufficient background explanations they may result in misinterpretations and misuse.

An additional overall choice regarding input data concerns the use of generic data or the use of product-specific data in the form

Table 2
Summary of the points of attention within assessment practice that leads to differences in EEG results.

Process steps according to EN 15978	Information required, based on EN 15978	Points of attention identified in international EEG literature and practice
Identification of the purpose of assessment Specification of the object of assessment	Goal Intended use Functional equivalent	Goal and intended use of study affects subsequent methodological choices, e.g. about functional equivalent, system boundaries etc. Lack of international definitions and terminology to describe functional and technical requirements (e.g. zero-emission-building) as well as referencing units (definitions of m2)
	Reference study period	Reference study period set: 1. arbitrarily (as a numerical exercise to report annualised EEG results) 2. as the required service life of building (although no consensus exists on how to determine this)
	System boundaries	Variations in system boundaries at different levels: 1. selection of included building life cycle stages 2. selection of building model scope
	Description of the physical characteristics of the building	Uniqueness of building design and construction practice
Scenarios for the building life cycle	Description of scenarios for all periodic operations	Variations in available information on service life of materials and products Variations according to national practice, guideline and/or regulation, for instance: 1. waste management 2. building site regulations
	Description of scenarios for all included life cycle stages	
Quantification of the building and its life cycle	Quantification of all net and gross amounts of materials and products in the building's life cycle	Potential simplifications of the building scale LCI
	Type of LCI data	Variations in sources and their level of detail (drawings, BIM data etc.)
Selection of environmental data and other information	Environmental data used for calculations	Representativeness of data Generic or product specific data System boundaries of database(s): 1. including/excluding carbon storage in biomaterials 2. width of included input and output substances and resources in data's modelling background
Calculation of the environmental indicators	Choice of indicators and characterisation factors	CED definition: 1. primary or end-use energy 2. including/excluding feedstock energy 3. primary energy based on upper or lower heating value of chemical energy sources 4. point of measurement for renewable energy sources 5. primary energy content from uranium based energy GWP definition: 1. included GHG emissions 2. characterisation factors used for GHG other than CO2 3. temporal scope of GHG emissions
	Calculation method for total life cycle impacts	Input-output, hybrid or process based modelling approach of data

of EPDs. The choice of one or the other option may again reflect at which point of the design stage the assessment is carried out. At early stage design, for instance, the exact knowledge of the products that are going to be used in the building does not exist and thus generic data is needed for LCA modelling. However, even for assessments carried out at later stages of the building design where the specific products are indeed known, it may prove difficult to locate product specific EPDs for all materials in the building. Hence, generic data or data from other databases is, in the assessment practice, used to fill in the data gaps, creating uncertainty as to whether system boundaries etc. are consistent in the different data [75].

3.2.6. *Calculation of the environmental indicators*

The specifics of the calculation of environmental indicators also lie as inherent choices in the Annex 57 case studies through the use of specific databases. Of the 19 databases used in the Annex 57 case study collection, one is input-output based (refer JP studies) and the rest are process based. This modelling approach in the Japanese case studies thus partly explains the studies being in the higher range of the reported EEG results.

Although the impact assessment scope of EEG studies focuses on primary energy use and GHG emissions as indicators, the exact definitions of these indicators can be ambiguous and/or missing documentation, as mentioned in Section 1.2.2. The reporting template of The Annex 57 case studies was not detailed enough to convey this level of detail for the databases, and not even the background information for the case studies report the definitions. This in turn could be the consequence of the lack of harmonisation of indicators as mentioned by Frischknecht et al. [41].

3.3. *Points of attention in the use of EEG results*

A range of significant, methodological parameters in the assessment practice are presented in the previous Sections 1.3 and 3.2 and summed up in Table 2. It is a deliberate choice from the authors of this paper not to address the exact numerical influence on EEG results caused by the different parameters, but rather to identify the points of attention to keep in mind when using EEG studies from external and/or international sources. The deliberate lack of focus on exact numerical influence is based on the fact that the many different methodological parameters interact. Hence, the numerical expressions of significance to EEG results will be specific only to the study in question due to the uniqueness of the exact methodological parameters of study.

The identified significant parameters of methodological importance summed up in Table 2 are key elements in order to use, interpret and transfer existing knowledge about EEG profiles and design strategies in buildings. Research have in several cases advocated for increased transparency in studies of embodied impacts [13]. With the points of attention described in Table 2, this paper now provides a structured overview of the methodological choices that is seen to influence EEG results and hence need additional focus in terms of transparent descriptions.

4. Conclusions and recommendations

In this paper, we systematically explain and analyse the methodological implications on quantitative EEG results obtained in the Annex 57 case studies and we point to the areas of assessment practice where there is a need for clarification of the LCA methodological approaches applied in the building sector. The analysis of methodological parameters is structured by the assessment calculation method provided by the EN 15978 standard. The content of Table 2 thus presents an analytical approach that follows the stepwise methodological choices that are actually made in the building EEG assessment practice. Each of the six assessment process steps involves one or more methodological choices relevant to the EEG results.

In spite of a thorough standardisation format, assessments in practice are carried out in a multitude of ways. As exemplified in the Annex 57 case study collection, the stated purposes of the building EEG assessments are one of the drivers leading to these differences in practice and results. There is nothing wrong in the differences as such, but it increases the risk of misinterpretations if EEG case studies are used for inspiration in design practice or even in regulation without taking into account the influence from specific methodological choices. This shows that a common standard cannot suit all purposes, although it provides general guidance of practice. For individual studies, existing standards serve well as foundational guidelines within which to explore the environmental significance of a building and its life cycle. However, a high degree of detailed standardisation is appropriate for some purposes where horizontal comparison with other studies is inherent, e.g. certification and in the development of building regulations. Based on EEG assessments in practice, it is thus recommended to develop standards or guidelines that target specific contexts of purpose, e.g. national certification or regulatory purposes. These could well be inspired by the recommendations developed by Annex 57 for uniform definitions and templates which improve the description of system boundaries, completeness of inventory and quality of data, and consequently, the transparency of embodied impact assessments.

The diversity of EEG study practice impairs the direct use of results for horizontal comparisons or as inspiration for low-EEG design solutions. The transparency of reported studies is instrumental using the experience gained and to transfer knowledge to other cases. Furthermore, the transparency needs to apply to the specific areas of the study that are sensitive in terms of affecting the generated results. In this study, the methodological parameters which influence to EEG have been systematically addressed and are listed as points of attention in Table 2. For EEG study practitioners, it is recommended to address these points so as to ensure the correct understanding and use of a particular case study by a third party. For design practitioners seeking inspiration for low-EEG building design, it is recommended to evaluate existing, inspirational studies in light of the points of attention in Table 2 that clarify the choices that may affect results in a different methodological context. The combination potentials between these many methodological parameters signifies a multitude of ways in which the outcome of EEG studies are affected. Further research is needed to determine the quantitative significance of each of the methodological parameters listed in this paper. In light of the increasing efforts of regulation bodies and the building sector towards reducing EEG from buildings, awareness of these significant parameters is crucial in order to interpret and transfer existing knowledge about EEG profiles of and design strategies for buildings. The EEG resultsand identified methodological parameters presented in this paper will support the informed uptake of EEG and life cycle considerations in the building and construction sector and lead to the development of EEG regulation.

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Appendix A.

Case study	Database	RSP	Product stage			Construction process stage		Use stage					End-of-Life				Next product system	Main concept	Type
			Raw material supply	Transport to manufacturer	Manufacturing	Transport to building site	Installation into building	Use	Maintenance	Repair	Replacement	Refurbished	Deconstruction	Transport to EoL	Waste processing	Disposal	Reuse, recovery or recycling potential		
Austria																			
AT1	baubook eco2soft	100	x	x	x						x	x						New	Office
AT2	baubook eco2soft	100	x	x	x						x	x						New	Residential
AT3	baubook eco2soft	100	x	x	x						x	x						New	Office
AT4	EcoBat	60	x	x	x						x		x			x		Refurbished	Residential
AT5	Baubook eco2soft	100	x	x	x						x	x						New	Residential
AT6	Ökobau 2009	50	x	x	x						x				x	x		New	Office
Switzerland																			
CH1	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH2	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH3	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH4	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH5	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	School
CH6	EcoInvent 2.2	60	x	x	x						x				x	x		New	School
CH7	EcoInvent 2.2	60	x	x	x						x				x	x		New	School
CH8	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH9	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH10	EcoInvent 2.2	60	x	x	x						x				x	x		New	Residential
CH11	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH12	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH13	EcoInvent 2.2	60	x	x	x						x				x	x		Refurbished	Residential
CH14	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential
CH15	EcoInvent 2.2	60	x	x	x						x			x		x		New	Residential
Germany																			
DE1	Ökobau 2011	50	x	x	x						x				x	x	x	New	School
DE2	Ökobau 2011	50	x	x	x						x				x	x	x	New	School
DE3	Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential
DE4	Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
Denmark																			
DK1	PE int	50	x	x	x						x				x	x	x	New	Office
DK3a	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential
DK3b	ESUCO/Ökobau 2011	150	x	x	x						x				x	x	x	New	Residential
DK3c	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential
DK3d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Residential
DK3e	ESUCO/Ökobau 2011	50	x	x	x						x	x			x	x	x	New	Residential
DK4a	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4b	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4c	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4d	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4e	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4f	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
DK4g	ESUCO/Ökobau 2011	50	x	x	x						x				x	x	x	New	Office
Italy																			
IT2	EcoInvent	50	x	x	x				x		x		x	x	x	x	x	Refurbished	Residential
Japan																			
JP2a	(Not specified)	–	x	x	x													New	Residential
JP2b	(Not specified)	–	x	x	x													New	Residential
JP3	Various	60	x	x	x	x	x				x	x	x	x	x	x		New	Residential
JP4	IO table Japan	60/100	x	x	x													New	Office
JP5	IO table Japan	60	x	x	x	x	x	x		x	x	x	x					New	Office
JP6	IO table Japan	50/100	x	x	x	x												New	Office
JP7	IO table Japan	–	x	x	x	x	x				x	x	x	x				New	Office
South Korea																			
KR3	KOR LCI	50	x	x	x	x	x									x		New	Office
Norway																			
N01	EcoInvent	60	x	x	x						x							New	Residential
NO2	EcoInvent	60	x	x	x						x							New	Office

NO4	EPD	60	x	x	x	x									New	Residential
NO9	EcoInvent	60	x	x	x				x						New	Residential
Sweden																
SE2a	EcoInvent, BECE	50	x	x	x										New	Residential
SE3	EcoEffect, BEAT, EcoInvent	50	x	x	x										New	Residential
SE4a	EcoEffect, BEAT, EcoInvent	50	x	x	x										New	Residential
SE4b	EcoEffect, BEAT, EcoInvent	50	x	x	x										New	Residential
SE5	EcoEffect, BEAT, EcoInvent	50	x	x	x										New	Office
SE6	EPD, Ökobau 2013, EcoInvent, KBOB	1							x						Refurbished	Office
SE7	IVL Miljödata, EPDs, EcoInvent, KBOB, ICE	50	x	x	x	x	x	x		x	x	x	x	x	New	Residential
United Kingdom																
UK4	BATH ICE, ECEB	68	x	x	x	x	x	x	x	x	x	x	x	x	New	School
UK5	ICE, EcoInvent, USLCI	20	x	x	x	x	x								New	Residential

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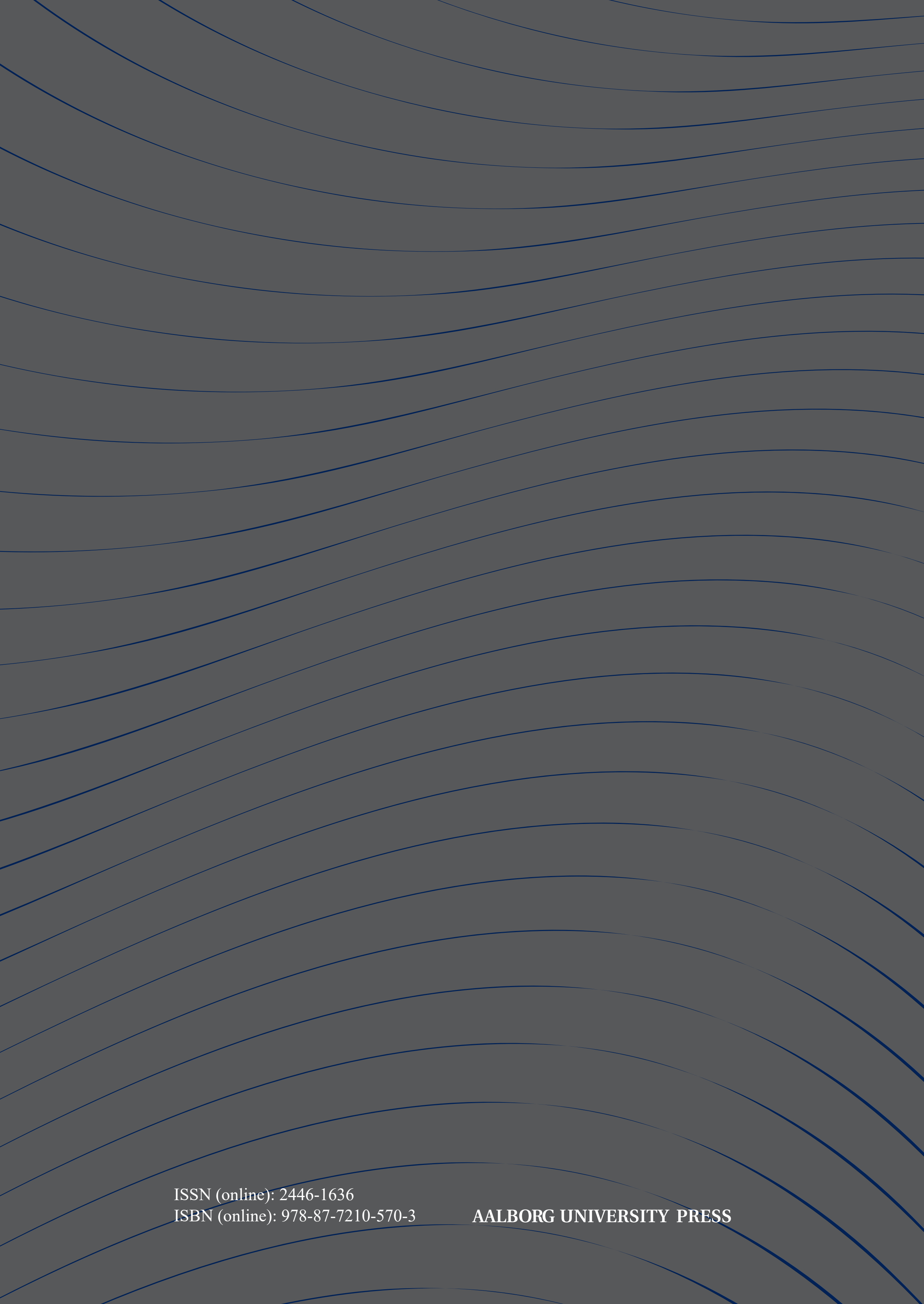

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