Qualifying Circular Economy in Building Design Practice

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QUALIFYING CIRCULAR ECONOMY IN BUILDING DESIGN PRACTICE

DEVELOPING LIFE CYCLE ASSESSMENT DESIGN CONCEPTS THAT SUPPORT IMPLEMENTATION OF CIRCULAR ECONOMY IN THE BUILDING SECTOR

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AALBORG UNIVERSITY
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ENGLISH SUMMARY

Failure to live within our planet’s boundaries has gained increased attention by the general public, companies and governments. The building sector has in recent years occupied an increasing part of the transition towards environmental sustainability due to its great share of material consumption, waste and environmental impacts. Current European and national policies have promoted circular economy (CE) to narrow, slow and close resource loops targeting net-zero-emission buildings by the year 2050. Hence, a radically different approach is needed for building and construction activities.

Developing and applying environmental CE design and decision-making tools and assessment methods are critical for reducing material consumption, waste and environmental impacts from buildings. This dissertation provides the Danish building sector with an overview of state-of-the-art CE design and construction strategies. It further presents environmental impact profiles of contemporary, prevalent Danish building types and different CE design and construction strategies. This dissertation critically evaluates the appropriateness of the current life cycle assessment (LCA) practice for stimulating CE in the building sector and further develops an existing LCA approach to closer align it with the CE concept. Finally, the dissertation provides environmental design guidelines for designing CE building components.

Sixteen CE building design and construction strategies were synthesised from existing literature, in which designing for assembly/disassembly (DfD), conscious material selection/substitution and designing for adaptability/flexibility proved to be the most prevalent strategies. It was found that the strategies connected in ways that allow one strategy to enhance another. Some strategies may be more suitable for some buildings, components and materials than for others. The evaluated literature also revealed a lack of knowledge about the environmental performance of the strategies to base strategy choices on. Moreover, to base strategy choices on is lacking and that a stronger link is needed between research and industry to progress the transition to a circular economy.

An LCA comparison of four different concrete building types built in Denmark finds that production, replacements and end-of-life account for 58%-68%, 11%-27% and 13%-21% of the buildings’ embodied greenhouse gas (GHG) emissions respectively. Thus, CE initiatives should be directed at reducing immediate emissions from production and emissions from replacements that happen prior to the climate targets for 2050. However, CE initiatives should not neglect facilitating the notable reduction potentials (16%-34%) from the second use of materials at the buildings’ end-of-life. Substantial embodied greenhouse gas reductions (14%-36%) can be achieved via combining a handful of CE initiatives, for example reuse of the concrete structure, recycling the roof felt and substitutions with wood and recycled aluminium. However, the magnitude of the savings achievable is dependent on the building context. Additional building types,

such as steel and wood structures, should be further investigated to support the transition to a CE.

An analysis of the LCA practice reveals how different environmental impact distribution approaches favour certain CE strategies over others. The dissertation finds that the current LCA practice in the building sector, following the European standards, is questionable for assessing CE due to its limited focus on single cycles and discouragement of DfD. Dividing the impact of shared components and materials over the number of cycles that share them can stimulate the multi-cycling concept of CE by creating shared responsibility as well as benefits for all cycles. In that regard, the dissertation further develops an existing approach to improve applicability and to closer align it with the CE concept and create an incentive for applying CE in the building sector. Reducing the uncertainty linked to the long lifespan of buildings and multiple cycles of a CE should be further investigated.

An LCA and material flow analysis (MFA) of five variants of a structure applying fundamentally different circular strategies showed that the performance of strategies depends on the set scenarios and timeframe of the assessment. The best performance was achieved when combining life-prolonging design strategies with other strategies such as bio-materials, resource efficiency and multiple cycles after end-of-use. Further, the dissertation highlights how single-indicator and multi-indicator assessments can lead to different results and thereby also design decisions. From the analysis, a set of design guidelines are recommended for designing circular building components. Additional CE design and construction strategies, as well as combining potentials of different strategies should be further investigated to support responses to global challenges such as climate change and resource scarcity.

The dissertation discloses the importance of integrating a temporal perspective into the LCA and benchmarking practice for CE. The increasing uncertainty over buildings' long lifespans and multiple future cycles of a CE may affect the long-term performance of both buildings and CE design and construction strategies. Furthermore, the benefits of CE strategies are available at different points in time. For example, design for disassembly realises emission reductions sometime in the future. Thus, CE efforts should focus on a timescale that responds to the urgency of different global challenges such as climate change and resource scarcity. Based on the urgency of climate change, the current reference-benchmarks approach in the building sector should be accompanied by budget-based benchmarks to limit the emissions allowed within the shrinking budget of emissions towards the net-zero-emission target in 2050.

While the research of the dissertation provides a stepping stone towards a building sector in balance with planetary boundaries, development and implementation of CE design and construction strategies and solutions as well as CE LCA approaches must be radically stepped up in the years to come.

DANSK RESUME

Overskridelse af jordens planetære grænser har fået øget opmærksomhed af både offentligheden, virksomheder og regeringer. Byggesektoren har i de senere år fyldt en større del af konverteringen til miljømæssig bæredygtighed på grund af sektorens store andel af verdens materialeforbrug, affald og miljøpåvirkninger. I europæisk og national politik bliver cirkulær økonomi (CØ) fremhævet, for at stramme, sænke og lukke ressourcekredsløb med et mål om klimaneutrale bygninger i 2050. Det kræver dog radikale ændringer af den nuværende bygge- og anlægspraksis.

Udvikling og implementering af CØ design- og beslutningsværktøjer samt miljøvurderingsmetoder er afgørende, for at reducere bygningers materialeforbrug, affald og miljøpåvirkninger. Afhandlingen tilvejebringer den danske byggesektor med en oversigt over CØ design- og konstruktionsstrategier samt miljøpåvirkningsprofiler på nybyggede bygningstyper i Danmark og forskellige CØ design- og konstruktionsstrategier. Derudover vurderer afhandlingen, hvor hensigtsmæssig den nuværende livscyklusvurderingspraksis er, i forhold til at stimulere CØ i byggesektoren. På baggrund af vurderingen videreudvikler afhandlingen en eksisterende metode, for at knytte metoden tættere til CØ-konceptet. Til sidst kommer afhandlingen med en række designanvisninger til cirkulære bygningskomponenter.

Igennem et systematisk litteraturstudie bliver seksten CØ design- og konstruktionsstrategier sammenfattet. Litteraturstudiet viser, at design for adskillelse (DfD), bevidste materialevalg og design for fleksibilitet er blandt de mest udbredte strategier. Strategierne viser sig at være knyttet på en sådan måde, at en strategi kan facilitere andre strategier, og nogle strategier er mere egnede til specifikke bygningstyper, byggekomponenter og byggematerialer. Den gennemgåede litteratur afslører også, at der mangler viden om strategiernes miljøpræstation, som valget af strategier kan baseres på, og at der er behov for et stærkere samarbejde mellem forskning og industri for at fremme CØ.

En sammenligning af fire forskellige beton byggerier opført i Danmark viser at produktion, vedligeholdelse og bortskaffelse står for mellem 58%-68%, 11%-27% og 13%-21% af bygningernes drivhusgasudledning. Derfor bør CØ-tiltag fokusere på, at reducere drivhusgasser fra produktionen og vedligeholdelse, der forekommer i årene op til klimamålsætningerne for 2050. Dog bør CØ tiltag også fokuserer på at facilitere reduktionspotentialet (16%-34%), der kan indfries ved videre brug af byggematerialerne ved bygningens endte levetid. Der kan opnås betydelige drivhusgasreduktioner, ved at kombinere en håndfuld af CØ-tiltag. For eksempel, genbrug af betonkonstruktionen, genanvendelse af tagpap samt brug af træ og genbrugsaluminium. Besparelsen er imidlertid afhængig af den enkelte bygning. Flere undersøgelser bør omfatte andre bygningstyper så som stål- og trækonstruktioner, for at understøtte overgangen til CØ.

En analyse af den nuværende LCA-praksis viser, hvordan forskellige måder at fordele miljøpåvirkninger på resulterer i, at visse CØ-strategier bliver favoriseret. Afhandlingen finder frem til, at den nuværende LCA-praksis i byggesektoren, der følger de europæiske standarder, er tvivlsom i forhold til at vurdere CØ på grund af dens begrænsede fokus på enkelte livscyklusser og demotivering af DfD. CØ-tankegangen om flere livscyklusser kan motiveres ved, at fordele miljøpåvirkningerne fra komponenter og materialer mellem cyklusserne, der deler dem således, at der etableres et fælles ansvar og fælles gevinster for alle cyklusser i systemet. I den forbindelse videreudvikler afhandlingen en eksisterende LCA-metode, for at forbedre anvendeligheden, knytte metoden tættere til CØ-konceptet og skabe et incitament til CØ i byggesektoren. Det bør undersøges nærmere hvordan usikkerheden, der opstår i forbindelse med bygningers lange levetid og flere livscyklusser i forbindelse med CØ, kan reduceres.

En LCA og materiale flow analyse (MFA) af fem varianter af en bygnings konstruktion, der anvender forskellige CØ-strategier, viser at strategiernes præstation er afhængig af de fastsatte scenarier og tidsrammen for analyserne. Den bedste præstation opstod, når levetidsforlængende tiltag blev kombineret med andre strategier, for eksempel brug af biomaterialer, ressourceeffektivitet og flere livscyklusser ved endt brug. Derudover fremhæver afhandlingen, hvordan enkelt- og multiindikatorvurderinger kan føre til forskellige resultater og dermed også forskellige design beslutninger. Af analysen anbefales en række retningslinjer for design af cirkulære byggekomponenter. Flere CØ-strategier såvel som kombinering af potentialet fra flere CØ-strategier bør undersøges yderligere, for at hjælpe med at besvare globale udfordringer som for eksempel klimaforandringer og ressourceknaphed.

Afhandlingen demonstrerer også vigtigheden af at integrere et tidsmæssigt perspektiv i LCA- og benchmarking-praksis. Usikkerheden, der knytter sig til bygningernes lange levetid og fremtidige livscyklusser i forbindelse med CØ, kan påvirke både bygningernes og CØ-strategiernes langsigtede præstation. Derudover er fordelene ved forskellige CØ-strategier tilgængelige på forskellige tidspunkter. For eksempel realiserer DfD emissionsreduktioner engang i fremtiden. CØ-tiltag bør være tidssvarende i forhold til alvoren af forskellige globale udfordringer som for eksempel klimaforandringer og ressourceknaphed. På baggrund af klimaændringerne bør den nuværende reference benchmarkmetode i byggesektoren ledsages af budget-baserede benchmarks, for at begrænse mængden af tilladte emissioner indenfor et konstant indsnævrende emissionsbudget, for at nå målet om klimaneutralitet i 2050.

Forskningen giver et springbræt mod en byggesektor, der er i balance med de planetære grænser, men udvikling og implementering af både CØ design- og konstruktionsstrategier og -løsninger samt CØ LCA-metoder skal intensiveres i de kommende år.

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PREFACE

This dissertation is an original, unpublished and independent work by the author, Leonora Charlotte Malabi Larsen, as a result of an industrial PhD project carried out at the Department of the Built environment at Aalborg University under the Faculty of Engineering and Science from 2017 to 2020. The project was carried out in close collaboration with the Danish contracting company MT Højgaard and the University of Southern Denmark with funding from the Innovation Fund and MT Højgaard's scholarship for employees. The dissertation is based on a core collection of four publications mentioned in Chapter 1 with common focus on building design and construction strategies under the circular economy (CE) concept and the life cycle assessment (LCA) method. The four core publications are complemented by a set of other, related publications written during the PhD project. These complementary publications touch upon different topics that, in different ways, put the core set of publications into perspective. The complementing publications are as follows:

Topic: CE in the building sector

- "Potential of Circular Economy in Sustainable Buildings". Eberhardt, L; Birkved M; Birgisdottir, H. In: IOP Conference Series: Materials Science and Engineering, 2019.

Topic: LCA of CE building design and construction strategies

- "Life cycle assessment of a Danish office building designed for disassembly". Eberhardt, L; Birgisdottir, H; Birkved M. In: Building Research & Information, 2018.
- "Comparing life cycle assessment modelling of linear vs. circular building components". Eberhardt, L; Birgisdottir, H; Birkved M. In: IOP Conference Series: Earth and Environmental Science, 2019.
- "Towards circular life cycle assessment for the built environment: A comparison of allocation approaches". Eberhardt, L; van Stijn, A; Rasmussen, F; Birkved, M; Birgisdottir, H. IOP Conference Series: Earth and Environmental Science, 2020.

Topic: Temporal perspective of CE in the building sector

- Dynamic Benchmarking of Building Strategies for a Circular Economy. Eberhardt, L; Birgisdottir, H; Birkved M. In: IOP Conference Series: Earth and Environmental Science, 2019.

Topic: Environmental impact hotspots from existing building LCAs

- Tracing the environmental impact origin within the existing building portfolio of prevailing building typologies. Rønholt, J; Eberhardt, L; Birkved M; Birgisdottir, H; Bey, N. In: IOP Conference Series: Earth and Environmental Science, 2019.

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Finally, I would like to thank the countless industry stakeholders that I have been in contact with for the past three years for their valuable collaboration and input that has continuously helped shape my work.

GLOSSARY

ADPe	Abiotic depletion potential for elements (environmental impact category measured in kg Sb eq.)
ADPf	Abiotic depletion potential for fossil resources (environmental impact category measured in MJ)
AP	Acidification potential (environmental impact category measured in kg SO_2 eq.)
CE	Circular economy
CE LD	LCA allocation approach (Circular economy linear degressive)
CFF	EoL calculation method in PEF (Circular Footprint Formula)
CML	Life cycle impact assessment method (Centre for Environmental Studies)
DfD	Design for disassembly
DGNB	Building certification system (Deutsche Gesellschaft für Nachhaltiges Bauen)
EMF	Ellen MacArthur Foundation
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
EP	Eutrophication potential (environmental impact category measured in kg PO_4 eq.)
EPD	Environmental product declaration
EU	European Union
FAETP	Freshwater aquatic ecotoxicity potential (environmental impact category measured in kg 1.4-DB eq.)
GHG	Greenhouse gas emissions
GWP	Global warming potential (environmental impact category measured in kg CO_2 eq.)
HTP	Human toxicity potential (environmental impact category measured in kg 1.4-DB eq.)
LCA	Life cycle assessment
LD	Allocation approach (linear degressive)
LEED	Building certification system (Leadership in Energy and Environmental Design)
MAETP	Marine aquatic ecotoxicity potential (environmental impact category measured in kg 1.4-DB eq.)
MFA	Material flow analysis
MCDA	Multi criteria decision analysis

ODP	Ozone depletion potential (environmental impact category measured in kg CFC-11 eq.)
PEF	Product Environmental Footprint
POCP	Photochemical ozone creation potential (environmental impact category measured in kg C_2H_4 eq.)
RSP	Reference study period
TETP	Terrestrial ecotoxicity potential (environmental impact category measured in kg 1.4-DB eq.)
UN	United Nations
VRP	Value Retention Process or R-imperative (e.g. reduce, reuse and recycle)

CHAPTER 1. INTRODUCTION

1.1. ENVIRONMENTAL CHALLENGES OF THE BUILDING SECTOR

Natural resource use has tripled since 1970 (IRP, 2019) and is projected to more than double by 2060 from 79 Gt in 2011 to 167 Gt (OECD, 2019). Simultaneously, the proportion of non-renewable materials compared to renewable materials continues to grow (IRP, 2017). Consequently, global waste is expected to increase by 70% by 2050 compared to current levels (Worldbank, 2018). Material management is estimated to account for more than 50% of all greenhouse gas (GHG) emissions (OECD, 2019). The atmospheric content of GHG from human activities continues to rise along with global temperature (IPCC, 2018). 2019 was the second warmest year on record (UN, 2020). Failure to live within the boundaries of our planet has greatly occupied the minds of the general public, companies and governments within recent years. However, progress towards many environmental targets is still lacking (EEA, 2019).

Recently, the building sector has increasingly become part of the environmental transition. On a global scale, the built environment contributes 39% of CO_2 emissions, 11% of which comes from manufacturing building materials and products (International Energy Agency, 2019). In addition, buildings use approximately 40% of all extracted resources (by volume) and in return generate 40% of solid waste streams in developed countries (by volume) (IRP, 2017). As a great amount of all the materials extracted in human history are locked in the built environment (Kibert, 2007), buildings may become a major temporary material stock to supply future demands. Emissions from the building sector are increasing in line with, among other factors, increased floor area and population growth (International Energy Agency, 2019). By 2050, the global building stock is expected to double (ibid). A different approach to planning, design, construction, maintenance, refurbishment and end-of-life of buildings will provide significant opportunity to pursue sustainability-oriented goals such as the UN Sustainable Development Goals (SDGs) on climate action and responsible consumption and production (UN, 2020).

1.2. TOWARDS A CIRCULAR BULDING SECTOR

In Europe, efforts to reduce buildings environmental impact have primarily focused on reducing operational energy consumption, resulting in the development of energy-efficient buildings (Malmqvist, Nehasilova, Moncaster, Birgisdottir, & Nygaard, 2018). Hence, the embodied environmental impacts of building materials (from production, construction, maintenance and disposal) can be considered as representing a significant and increasing share of a building’s life-cycle-aggregated environmental impact (Röck et al., 2020). In some Danish cases, the embodied GHG emissions from building materials account for more than 70% of the building’s life-cycle aggregated environmental impacts. In view of this development, CE is being regarded as an important step to continue the effort of reducing building-related GHG emissions while reducing resource consumption and waste generation (Pomponi & Moncaster, 2017).

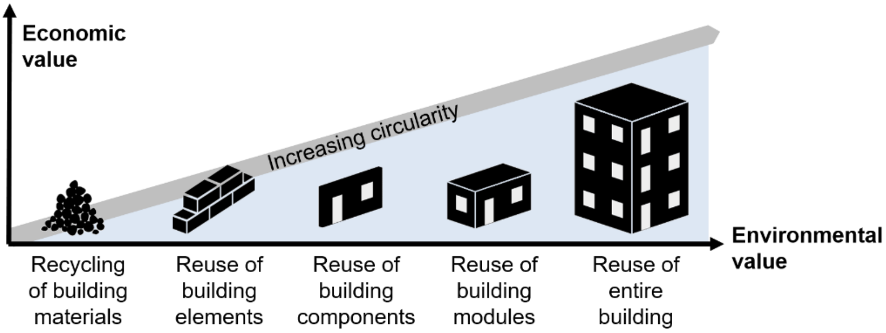


Figure 1. Conceptualisation of the CE concept in the built environment. From (Eberhardt, Birgisdóttir, & Birkved, 2018b).

CE is considered to be a restorative and regenerative approach in which emissions, resource use and waste generation are reduced through the CE principles of narrowing (efficient resource use), slowing (temporally extended use) and closing (cycling) current and future resource loops (Bocken, de Pauw, Bakker, & van der Grinten, 2016; Geissdoerfer, Savaget, Bocken, & Hultink, 2017). In doing so, CE seeks to preserve finite stocks of natural resources and ensure a renewable flow of products and materials, keeping them at their highest utility and value for as long as possible (see Figure 1) (Ellen MacArthur Foundation, 2012, 2015a; European Commission, 2020a). The CE is operationalized through value retention processes (VRPs) (also known as R-imperatives), such as, refuse, reduce, reuse, repair, refurbish, recycle and recover, of which some result in re-loops (Reike et al., 2018). Re-loops can be aided by a multitude of different design strategies such as design for disassembly, adaptability, durability, use of low-impact materials, reducing the amount of materials use etc. (European Commission, 2020b). Multi-cycling is a key aspect of CE (i.e. not only to focus on single re-loop process but also on a sequence of multiple re-loops (Blomsma, Kjaer, Pigosso, McAloone, & Lloyd, 2018; Mestre & Cooper, 2017). Thus, re-loops can create cascading systems where building components or materials are used in a series of different applications inside and outside of a building, both locally and globally (Rehberger & Hiete, 2020). In recycling research, closed loop refers to recycling into the same material or product and open loop refers to recycling into other materials and products (Koffler, 2018). However, in a CE, open or closed loops are often also understood in relation to their supply chain (French & Laforge, 2006). In this context, open loops are realised by parties other than the industry (parties) involved in original production and closed loops are realised by the industry (partners) involved in original production. Thus, CE represents a shift in mindset from end-of-pipe solutions, where construction and demolition waste is managed at the buildings' end-of-life (EoL) to more holistic and preventive whole life cycle management approaches.

CE has more recently been actively promoted in international policy. At European level, the European Commission is committed to transition to a CE (European Commission, 2020a). This includes transitioning to a circular built environment among others praising reuse of building components (ibid) and net-zero-emissions buildings by 2050 (European Commission, 2019b). In recent years, a CE package and CE action plan (European Commission, 2020a) have been issued, and nearly 1 billion euros from the EU Research and Innovation Programme, Horizon 2020, has been invested from 2018-2020 to support CE ambitions (European Commission, 2017). Furthermore, CE aspects have been integrated into the recent EU waste directive (European Parliament and the Council of the European Union, 2018).

At national level, interest for CE in the Danish built environment was sparked when the UK-based non-governmental organization, the Ellen MacArthur Foundation (EMF) published a case study on the potential of Denmark as a CE (Ellen MacArthur Foundation, 2015b). The report identified construction and real estate as the sector with the highest potential for CE. Following the report, the Danish government launched an advisory board for CE in 2016. In 2017, the board presented 27 recommendations, including for the building sector. As a follow-up, the Danish government launched their CE strategy in 2018. As part of this strategy, a voluntary sustainable building class in the Danish building code has recently been launched (Danish Transport and Construction Agency, 2020). In parallel with these developments, Denmark's first circular social housing project, Circle House, was developed from 2017-2020, were 90% of the building materials can be recycled without loss of value (Partners Circle House, 2018). Furthermore, the Danish government climate council has recently recommended introducing a 'polluter pays' CO_2 tax in 2030 (DKK 1,500 per tonne CO_2 emitted) to reach a 70% CO_2 reduction in 2030 (Climate Council, 2020), providing a strong motivation to find ways of reducing the embodied GHG emissions from building materials. Furthermore, there is a wish to accelerate CE in the Danish building sector through closer collaboration between academia and industry to combine theoretical knowledge with practice (Innovation Fund Denmark, 2020). Succeeding this industrial PhD, 15 new industrial PhDs are being funded to develop circular solutions and business models based on existing and ongoing CE knowledge, developments and projects in the building sector (ibid).

Motivation for implementing CE in the European and Danish building sector is high, but requires a focused effort and fundamental changes in practices in the entire sector.

1.3. CHALLENGES OF IMPLEMENTING CE IN THE BUILDING SECTOR

Although different efforts have been made in recent years to implement CE at both European and Danish levels, the implementation of CE in building sector practice is limited in both scale and speed. Several challenges obstruct implementing CE in the building sector. However, one very crucial challenge is that there are still no readily available environmental CE design and decision-making tools and assessment methods to support implementation in the building sector. Four main problems and knowledge gaps have been identified pertaining to generating CE tools and assessment methods for the building sector. First, there is no commonly accepted definition of CE in the building sector (Hart, Adams, Giesekam, Tingley, & Pomponi, 2019). The CE concept is used to define a variety of different strategies (Kirchherr, Reike, & Hekkert, 2017), thus there are many options to design circular buildings, components and materials. Second, comprehensive knowledge about where the largest potential for reducing buildings' environmental impacts exist is still limited. Third, there are no well-established methods or approaches for how to quantify the environmental effects of CE (Sassanelli, Rosa, Rocca, & Terzi, 2019). Life cycle assessment (LCA) is an accepted method for assessing environmental impacts in the building sector (EN 15978, 2011). However, current LCA tools do not suffice in the design phase, among other things due to data intensiveness, lack of available data in the design stage, and decision makers' lack knowledge on how to perform and interpret LCAs (Cavalliere, Habert, Dell'Osso, & Hollberg, 2019; Means & Guggemos, 2015). Furthermore, current conventional LCA methods focus on analysing individual products and single life cycles (Ghisellini, Cialani, & Ulgiati, 2016). In contrast, the CE concept focuses on a systems perspective in which buildings, components and materials - potentially - have different and multiple use cycles, and life cycles (Blomsma et al., 2018; Rehberger & Hiete, 2020). The system perspective of CE introduces a problem of how benefits and burdens should be allocated between use cycles and life cycles to which there is no single widely accepted approach among the many existing different allocation approaches (K. Allacker et al., 2014). Fourth, although studies seeking to prove the environmental benefits of CE exist in the building sector (Ghisellini, Ripa, & Ulgiati, 2018; Nasir, Genovese, Acquaye, Koh, & Yamoah, 2017), there is still inadequate knowledge on which CE design options result in the best environmental performance (Andersen, Kanafani, Zimmermann, Rasmussen, & Birgisdóttir, 2020). Specific CE building cases and their implications are limited (Hossain & Ng, 2018; Hossain, Ng, Antwi-Afari, & Amor, 2020). Furthermore, CE strategies do not by default lead to environmental impact reductions (Gallego-Schmid, Chen, Sharmina, & Mendoza, 2020).

In light of the pressing global environmental challenges, these gaps may lead building designers to focus efforts on the less efficient CE strategies or optimizing building components and materials of less environmental importance.

1.4. THE BUSINESS PERSPECTIVE BEHIND THE PHD PROJECT

In recent years, policy makers and academia have acknowledged that a business perspective is important for achieving more sustainable buildings. As CE has a strong focus towards businesses compared to preceding concepts, it has gained a strong foothold in both policy, industry and academia over recent years, compared to antecedents such as industrial ecology.

For that reason, the research for this industrial PhD project was developed at MT Højgaard, a Danish contractor well-known for its 100-year-long history of large and complex building and infrastructure projects. The company has a tradition for innovation and research that is driven by a strong sense of social responsibility and ambition to continuously provide solutions for societal challenges.

As sustainability is high on the agenda in the Danish building sector, MT Højgaard realizes that failure to respond to the sustainability agenda will inevitably affect the company's future competitiveness. The popularization of CE by the EMF, (Ellen MacArthur Foundation, 2015b, 2016) motivated MT Højgaard to investigate possibilities of adopting the concept back in 2016. Together with industry stakeholders representing different links of the supply chain, MT Højgaard published the book 'Building a Circular Future' (Sommer & Guldager, 2016). The ideas from the book eventually led to the development of the Circle House project with MT Højgaard as one of the spearheads for the project (Partners Circle House, 2018). MT Højgaard found that substantially reducing buildings' environmental impacts requires early design stage optimisations, as 80% of a building's environmental impact, resource consumption, waste production and cost is based on decisions made in the early design stage (Winkler, 2011). In this regard, the contractor has unutilised knowledge about buildability and building materials because the contractor is often involved in the later design stages when many decisions are already fixed and cannot be changed. The motivation for initiating the industrial PhD project was therefore to gain research-based knowledge on how to develop a CE design and decision-support tool that would give the company a competitive advantage in the early design stages while ensuring more resource-efficient projects without the client experiencing decreased added value of the project. Furthermore, the tool was to support a more sustainable building design and decision-making process without introducing further and potentially excessive complexity into the process.

Different features were discussed for such a tool:

- helps make quicker decisions on an informed basis to keep up with the fast pace of the design stage.
- assesses and documents a building's environmental footprint and influence the choice of materials
- shows reuse/recycling input/output of buildings

- simplifies LCA and makes LCA knowledge available for non-experts.

Because the company gets involved at different stages of a project (depending on the type of project), they needed a tool that can be used for optimization and dialogue in the design stages, as well as reporting and documentation in the later project stages. In parallel with the PhD project, the author of this dissertation has been involved with the continuous development of different tools at MT Højgaard that support and document the value of material choices based on the research findings of the core publications presented in this dissertation.

1.5. RESEARCH AIM, FOCUS AND QUESTIONS

In line with the nature of the industrial PhD project, the research aim, focus and questions of this dissertation reflect both the academic and commercial gap pertaining to implementation of CE in the building sector.

In summary, a design and decision-making basis is needed that reduces buildings' environmental impacts to support the transition of the building sector towards a CE. Developing such a basis requires identification of which building design and construction strategies support the CE concept (i.e. which to focus on) and how LCA can support the implementation of these strategies in the building sector. Therefore, this dissertation has a dual focus on building design and construction strategies employed under the CE concept and the LCA assessment method.

Hence, the dissertation aims to:

1. Provide the building sector with an overview of state-of-the-art CE building design and construction strategies
2. Identify, for the building sector, where the largest potential environmental impact reductions exist in buildings within a Danish context using LCA
3. Clarify, for the building sector, how the LCA method can be aligned with the CE concept
4. Determine which CE building design and construction strategies to focus on in the transition towards a circular built environment and develop CE design guidelines for the building sector

The main research question (MRQ) of the dissertation is:

MRQ: How can LCA support the implementation of CE principles in the building sector to reduce buildings' environmental impact potentials?

Sub-questions (SQ) that pertain to the main research question are:

SQ1: Which design and construction strategies are related to CE?

SQ2: Which life cycle stages, building components and materials induce the largest environmental impact potentials within prevailing Danish building types?
SQ3: How do different allocation approaches affect the LCA outcome and the incentive for CE when using them to assess different CE building design and construction strategies?
SQ4: Which CE design and construction strategies result in the largest environmental impact savings?

1.6. READING GUIDE

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

Publication 1: **Building design and construction strategies for a Circular Economy**. *Eberhardt, L; Birkved M; Birgisdottir, H.* In: Architectural Engineering and Design Management, 2020

Publication 2: **Circular Economy potential within the building stock – mapping the embodied greenhouse gas emissions of four Danish examples.** *Eberhardt, L; Rønholt, J; Birkved M; Birgisdottir, H.* In: Building Engineering, 2020

Publication 3: **Development of a Life Cycle Assessment Allocation Approach for circular economy in the built environment**. *Eberhardt, L; Birkved M; Birgisdottir, H.* Submitted to Sustainability, 2020.

Publication 4: **Environmental design guidelines for circular building components: the case of the circular building structure.** *Eberhardt, L; van Stijn, A; Birkved M; Birgisdottir, H.* Submitted to Environmental Management, 2020.

The research of this dissertation is placed within a pragmatic research setting with a dynamic and practice-related development approach fitting the academic and industrial scope of the research. Figure 2 illustrates how the four core publications answer the research question. Publication 1 develops the research framework for this dissertation by assessing which design and construction strategies are linked to the concept of CE for new buildings, and their level of application and readiness in a building context. Publication 2 assesses embodied GHG emissions hotspots of four commonly constructed building types in Denmark (a school, an office, a residential building and a hospital) and points towards CE design and construction strategies that should be in focus towards transitioning to a CE. Publication 3 deals with the alignment of the single life cycle perspective of conventional LCA with the system perspective of CE. Publication 3 also clarifies the influence of different allocation approaches on the assessment of circular building components and further develops an allocation approach, herein referred to as the CE LD approach, to enhance applicability, to closer align it with the CE concept, and to create an incentive for CE in the building sector. Publication 4 derives CE design guidelines from applying the developed CE LCA method from Publication 3 to five variants of a building structure.

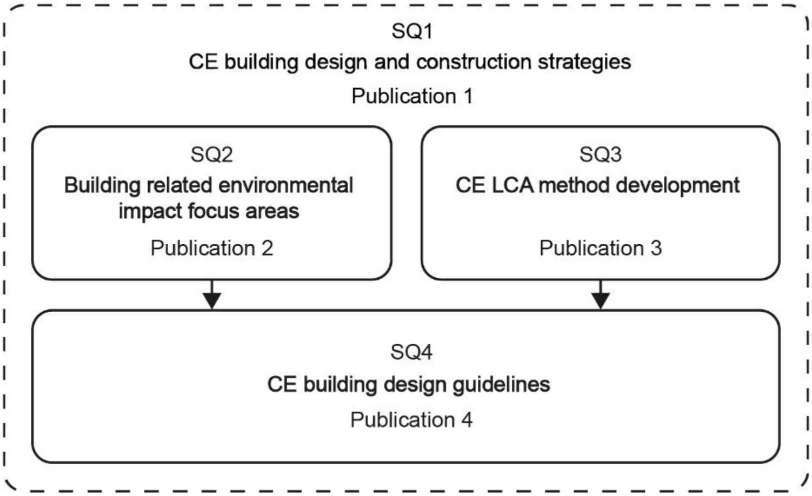


Figure 2. Research framework of the dissertation

Table 1 outlines the methods used for addressing the research aim, focus and questions. These are further elaborated in Chapter 3. Method.

Table 1. Methods applied in the different publications

Methods applied	**Publication**			
	1	**2**	**3**	**4**
Systematic literature review	x			
Case study		x	x	x
Life cycle assessment		x	x	x
Expert sessions			x	x
Sensitivity analysis			x	x
Material flow analysis				x

1.6.1. DISSERTATION OUTLINE

The dissertation is structured in six chapters. Chapter 2 outlines the state-of-the-art regarding circular economy and life cycle assessment in the building sector. Chapter 3 explains the research methods listed in Table 1 applied within the core publications. Chapter 4 presents the findings from the research in relation to the two focus areas of building design and construction strategies employed under the CE concept and the LCA assessment method. An additional outlook is provided in Chapter 5 as part of a discussion that puts perspective on the conclusions and future research recapped in Chapter 6. Chapters 2, 4 and 5 each provide a summary that allows for quick reading of the dissertation.

1.7. MAIN CONTRIBUTIONS

The main scientific and business contributions of this dissertation can be summed up as follows:

Scientific contributions:

- Identification of building and construction strategies under the CE concept, their level of application and readiness in the building industry
- Systematic comparison of the embodied GHG emissions profile of four different building types in Denmark
- Evaluation of the effect of different LCA allocation approaches on four different circular designed building components
- Development of an LCA method for building components that is closer aligned with the CE concept
- Comparison of the environmental impact performance of different CE design and construction strategies
- An environmental design guide that highlights important design considerations for designing circular building components

Business contributions:

- A structured mapping of the embodied GHG emissions profile of the company's prevailing building types
- Design guidelines to help the company develop new building concepts on an informed basis
- A structured LCA mapping method for building projects
- Development of different LCA tools containing CE design solutions specific for the company's business model and strategy that can be used at different project stages, for example the design phase and tendering phase of a project.

CHAPTER 2. STATE-OF-THE-ART

This chapter provides a general overview of state-of-the-art relevant to the research topic presented in Chapter 1. Here, existing concepts and relevant literature that further sum up and specify the identified research gap(s) that need(s) addressing in the current research work are elaborated on.

2.1. CIRCULAR ECONOMY IN THE BUILDING SECTOR

CE unites pre-existing scientific and economic concepts and schools of thought with shared qualities and characteristics under one name (Blomsma & Brennan, 2017; Hart et al., 2019). These concepts include decades of well-established research fields and schools of thought such as industrial ecology, eco-design and cradle-to-cradle etc. (Boulding, 1966; Stahel, 1982; Frosch and Gallopoulos, 1989; Pearce & Turner, 1990; Brezet & van Hemel 1997, Braungart & McDonough, 2002). However, the Ellen MacArthur Foundation conceptualized the concept in 2012 (Ellen MacArthur Foundation, 2012). From 2013-2018, academic publications within CE rapidly increased by 50% (Reike, Vermeulen, & Witjes, 2018). The publications include many literature reviews (Blomsma & Brennan, 2017; Ghisellini, Cialani, & Ulgiati, 2015; Ghisellini et al., 2016; Kirchherr et al., 2017; Lieder & Rashid, 2016), frameworks (Blomsma et al., 2018; Bocken et al., 2016; Mestre & Cooper, 2017; Potting, Hekkert, Worrell, & Hanemaaijer, 2017), tools (Harpa Birgisdottir et al., 2019; Dautremont, Jancart, Dagnelie, & Stals, 2019; Ellen MacArthur Foundation & Granta design, 2015; Leising, Quist, & Bocken, 2018; van Stijn & Gruis, 2019), including BS 8001, the world's first standard on CE (Pomponi & Moncaster, 2019) and additional standards are on their way from the International Organisation for Standardisation to create consensus on principles, terminologies, frameworks, business models, assessment methods etc. (ISO, 2019). Despite the growing CE interest, the bulk of new building projects is not yet moving towards CE. Although the building sector is consolidating previous knowledge in the field (Cheshire, 2016; Geldermans, 2016; Ness & Xing, 2017), it struggles to embrace CE practices that have successfully been implemented in other sectors (Hart et al., 2019; Pomponi & Moncaster, 2017). However, sectors and products differ, and as the existing body of knowledge primarily has a broad focus, it fails to match the complex nature of the building sector (Hart et al., 2019).

Compared to other sectors, the building sector has distinct institutionalized organisational, cultural and legal characteristics which make the sector very complex to operate within and introduce new conventions to. The building sector has its own design process, manufacturing techniques, supply chain, market mechanisms and financial arrangements (Hart et al., 2019). Unlike other products, buildings are complex, long-lived, dynamic and unique entities (Adams, Osmani, Thorpe, & Thornback, 2017; Hart et al., 2019). Building projects require input from a great number of stakeholders within a complex (global) supply chain. The supply chain is fragmented due to the discontinuity of stakeholders across a building's life cycle and the stakeholders' varying, contradicting and/or competing short-term project-based goals (Hart et al., 2019). Design and construction of buildings combines multiple processes that do not run in sequence but in parallel (Geldermans, 2016). The building sector also suffers from financial fragility due to low profit margins that reinforce unwillingness to take risks (Love, Edwards, & Irani, 2012). In many ways, these characteristics do not fit the facilitation of CE principles. Therefore, transitioning to a circular built environment requires a more tailored understanding and approach to the CE concept (Hart et al., 2019).

CE building research is still limited (Munaro, Tavares, & Bragança, 2020). Only a few frameworks have been specified for the building sector (Pomponi & Moncaster, 2017) and there is insufficient development of CE design guidelines and tools (Hart et al., 2019). Furthermore, existing studies tend to focus on individual dimensions of CE; emissions, resource or waste generation as well as narrowing, slowing or closing loops, not all of them in combination. CE research to date has largely focused on managing construction and demolition waste, resulting in high recycling rates (Adams et al., 2017; European Commission, 2008). Down-cycling still dominates over up-cycling (Di Maria, Eyckmans, & Van Acker, 2018; Hopkinson, Chen, Zhou, Wang, & Lam, 2019). However, CE advocates more ambitious long-term preventive and whole life-cycle initiatives. Few partial/full-scale CE building cases exist (Ellen MacArthur Foundation, 2016; Partners Circle House, 2018; F. N. Rasmussen, Birkved, & Birgisdóttir, 2019). Furthermore, environmental performance assessments of CE solutions in the built environment are scarce (Andersen, Kanafani, et al., 2020; Gallego-Schmid et al., 2020) and often focus on single VRPs e.g. reuse (Assefa & Ambler, 2017; Densley Tingley & Davison, 2012). This inhibits the development of CE targets and metrics for the building sector that can help catalyse progress.

Compared to its preceding concepts, the CE concept is still in its infancy (Hossain & Ng, 2018; Murray, Skene, & Haynes, 2017). This is evident from the abundance of significantly varying concept definitions and degrees of adoption that exist globally across sectors in both research and practice (Bocken et al., 2016; Kirchherr et al., 2017; Lieder & Rashid, 2016; Reike et al., 2018). The unresolved paradigmatic questions of CE make the concept susceptible to misinterpretation and misuse, potentially depriving CE of its underlying principles, impact and values (Kirchherr et al., 2017; Reike et al., 2018). This is no different in the building sector, where there is also no clear or accepted definition of the concept (Hart et al., 2019). Consequently, many different design and construction strategies are associated with the CE concept such as design for disassembly, adaptability, durability etc. The result is slow, incoherent and random CE progress with a small effect across the building sector. This fragmented development potentially prevents universal adoption of CE in the building sector. Hence, a deeper knowledge of the CE practices introduced in the sector is essential to identify which practices are currently being performed and which still need to be implemented or improved to establish a common direction for the entire sector.

2.2. LIFE CYCLE ASSESMENT IN THE BUILDING SECTOR

Design and decision-making tools are needed to support reducing environmental impacts, resource consumption and waste as well as implementation of CE in the building sector. LCA is a scientifically based and ISO-standardised method for assessing resource consumption and environmental impact potential of a given product, service or system over its entire life cycle (EN 15978, 2011; ISO 14040, 2008; ISO 14044, 2006; ISO 21931-1, 2010). In the building sector partial or full-scale LCAs are well-established in building certification systems such as DGNB, LEED and BREEAM. LCA of buildings has also gained increased interest from regulatory bodies around Europe. The Netherlands was the first country to introduce mandatory LCA on new buildings (Scholten & van Ewijk, 2013). In Denmark, LCA has been implemented into the recently launched voluntary sustainable building class in the Danish building code (Danish Transport and Construction Agency, 2020). By 2023, the sustainable building class will become mandatory along with performing LCA on all new buildings (ibid). The number of published and conducted LCAs related to case studies of buildings is growing continuously (Paleari, Lavagna, & Campioli, 2016). There is consensus that LCA can assess the environmental performance of CE (Pomponi & Moncaster, 2017). LCA has also been used in some recent CE studies (Genovese, Acquaye, Figueroa, & Koh, 2016; Ghisellini et al., 2015).

It is generally acknowledged that application of LCA in the early design stage has the most promising potential to reduce buildings' life cycle environmental impacts (Hellweg & Mila i Canals, 2014; Marsh, 2016; Meex, Hollberg, Knapen, Hildebrand, & Verbeeck, 2018). However, use of LCA to guide design decisions is challenging. The design process for a Danish building project is divided into a number of sequential sub-phases (i.e. programming phase, early design phase, basic design phase and detailed design phase) before construction (Danske ARK & FRI, 2017). Although the design process itself is linear, design tasks are run in parallel and are divided between different stakeholders. The further the design process gets, the more stakeholders get involved and the more complex the process becomes to coordinate (Urup, 2016). This results in late design changes and rework ultimately resulting in delays (ibid). Often, construction begins before the design is finished in order to meet deadlines, and this means that part of the detailed design phase overlaps the construction phase (ibid). Thus, the early design stage is restrained by great uncertainty about design and material decisions. In contrast, the rigorous analysis needed to support the credibility of a building LCA is very data-intensive and time-consuming (Anand & Amor, 2017). Hence, LCA is primarily used to assess the completed building's environmental impact potential rather than an iterative design and performance optimisation tool (Cavalliere et al., 2019). Simplifications of the method are needed to encourage the use of LCA in practical design (Anand & Amor, 2017). Design-stage LCA developments ranging from simplified/screening to advanced/detailed analysis to utilise the optimisation opportunities provided in the design stage are ongoing (Meex et al., 2018; Röck, Hollberg, Habert, & Passer, 2018).

Numerous building LCAs have been performed to date (Anand & Amor, 2017; Malmqvist et al., 2018; Pomponi & Moncaster, 2016). An opportunity exists to draw common conclusions from these LCAs. Such conclusions can help identify CE opportunities and assist future design decisions. Some systematic reviews and comparisons of existing building LCAs exist (H. Birgisdottir et al., 2017; Harpa Birgisdottir, Houlihan-Wiberg, Malmqvist, Moncaster, & Nygaard Rasmussen, 2016; John, 2012; König & De Cristofaro, 2012; Rønholt, Eberhardt, Birkved, Birgisdottir & Bey, 2019; Zimmermann, Andersen, Kanafani, & Birgisdóttir, 2020). However, comparing results of existing building LCAs is challenging. Among others things, the environmental performance of buildings depends on several interlinked attributes (Maslesa, Jensen, & Birkved, 2018). Buildings are a conglomerate of components and materials, each with their own life-cycle, characteristics, degradation, and replacement rates, and each providing different and/or several functions (e.g. simultaneous structural support and thermal insulation, or a combination of materials to fulfil one specific function) (Hart et al., 2019). Thus, components and materials can have both direct and indirect impacts on other functions, which affect environmental performance optimisation opportunities. This is often inadequately accounted for or reported in an unclear manner in current LCAs (Resch & Andresen, 2018). Furthermore, building LCAs widely differ in scope, life cycle stages, reference study periods (RSP), functional units, inventories databases, impact assessment methods and resulting conclusions (Harpa Birgisdottir, Houlihan-Wiberg, Malmqvist, Moncaster, & Rasmussen, 2016; Nygaard, Malmqvist, & Moncaster, 2018; Pomponi & Moncaster, 2016; Resch & Andresen, 2018; Röck et al., 2020). Consequently, building LCAs are not (easily) comparable (Erlandsson & Borg, 2003; R. Frischknecht, Birgisdottir, Chae, Lützkendorf, Passer, et al., 2019; Frischnecht, Ramseier, Yang, Birgisdottir, Chae, Lützkendorf et al. 2020). Thus, pointing towards the most effective CE strategy is challenging. Ongoing research aims to clarify and harmonise the method and scope of building LCAs (Harpa Birgisdottir, Houlihan-Wiberg, Malmqvist, Moncaster, & Rasmussen, 2016; R. Frischknecht, Birgisdottir, Chae, Lützkendorf, & Passer, 2019).

Some environmental building design guidelines have been developed (Andersen, Kanafani, et al., 2020; Harpa Birgisdottir et al., 2019). In addition, some circular environmental design guidelines have been developed for buildings (Andersen, Kanafani, Zimmermann, Rasmussen, & Birgisdóttir, 2020; Birgisdottir et al., 2019). However, for several reasons, existing guidelines are challenging to use for designing circular solutions. First, they primarily focus on conventional building design (Harpa Birgisdottir, Houlihan-Wiberg, Malmqvist, Moncaster, & Nygaard Rasmussen, 2016). Second, they build on conventional environmental performance assessment methods, were the focus of assessment is on single life cycles. Third, they are aimed at the over-complex building level or the limiting material level to reach sustainability goals, whereas few guidelines exist for the intermediate building component level (Hollberg, Lützkendorf, & Habert, 2019; Kanafani, Zimmermann, Birgisdottir, & Rasmussen, 2019). Fourth, they often focus on single circular design strategies (e.g. design for disassembly (Crowther, 2005; Densley Tingley & Davison, 2012), using bio-based materials (Gustavsson, Pingoud, & Sathre, 2006; Sathre & González-García, 2013)), and using secondary materials (Assefa & Ambler, 2017; Hopkinson et al., 2019; Sanchez & Haas, 2018)). Fifth, they tend to build on single impact indicators, neglecting other more complex and sometimes uncertain impacts of environmental importance (Malmqvist et al., 2018; Pomponi & Moncaster, 2016). Environmental design guidelines specifically targeting design of circular building components with multiple use cycles and life cycles are needed in practice.

2.3. ALIGNING LCA WITH CE

The European LCA standards focus on analysing individual products and single life cycles (Ghisellini et al., 2016; Hauschild, Rosenbaum, & Olsen, 2018), mismatching the multi-cycling aspect of CE. A recent systematic literature review found that comprehensive evaluations of the full life cycle of buildings or further extending it from cradle-to-grave to cradle-to-cradle towards effective adoption of CE are almost absent (Hossain et al., 2020).

The re-loop processes of CE (e.g. reuse, repair, refurbish, recycle and recover) result in shared processes and functions between more than one product system. Other researchers within the CE field suggest that the most appropriate way to deal with multi-cycling is to distribute impacts between the number of predicted cycles (C. De Wolf, Hoxha, & Fivet, 2020; Densley Tingley & Davison, 2012; Rehberger & Hiete, 2020). The question is how the environmental benefits and burdens from the shared processes and functions should be allocated between the different use cycles and life cycles, and this is widely discussed within the LCA field (Allacker et al., 2014; Koffler, 2018; Rehberger & Hiete, 2020; Schrijvers, Loubet, & Sonnemann, 2016). The building sector needs to provide the environmental impact potential of buildings they construct. However, in a CE building, parts can be initially used in one building but subsequently reused in another or repurposed outside of the building sector. This makes it difficult for the building sector to determine the impact of their building compared to the next. Practical experience with multi-cycling examples (e.g. design for disassembly) is still limited. However, incentive is needed to motivate designing for multi-cycling as well as participating in multi-cycling. Furthermore, questions arise about how to deal with the uncertainty of whether or not future cycles will actually occur, even though they have been designed to happen.

Some general allocation recommendations have been provided by standards such as ISO 14040, ISO 14044, EN 15804 and EN 15978. However, several competing allocation approaches exist. They can broadly be grouped into three common overarching approaches: 0:100 (‘end-of-life recycling), 50:50 (‘equal share’) and 100:0 (‘cut-off’) (Allacker et al., 2014). Confusion arises as these approaches are described in different ways within research literature emphasizing different processes and impacts to be allocated between life cycles. For example, the 100:0 approach is used for both allocation of EoL impacts (Allacker, Mathieux, Pennington, & Pant, 2017) and to address allocation of avoided burdens from substituted materials (Jones, 2009). Furthermore, different approaches are recommended for different products and loops (Schrijvers et al., 2016)

The EN 15978/15804 standards form the basis for the current European LCA practice for construction products and buildings. Here, the ‘cut-off’ approach is used with focus on current emissions following a ‘polluter pays’ principle i.e. the environmental impacts from virgin material production and recycling at EoL are entirely attributed to the cycle initially providing the material (Frischknecht, 2010).

In addition to the more commonly known allocation approaches, several competing approaches also exist. Some of these approaches attempt to find a more tailored approach for CE such as the Circular Footprint Formula (CFF) by the European Commission’s Product Environmental Footprint (PEF) aimed at all types of products, including building products (Zampori & Pant, 2019). The CFF aims to enable the assessment of all EoL scenarios possible (i.e. reuse, recycling, incineration with/without energy recovery and final disposal via landfill) for both open and closed loop systems in a consistent way (ibid). In contrast to existing allocation approaches, the CFF tries to accommodate both recycled content at the input side and recyclability at EoL (ibid). It further considers the change in material quality between cycles. The CFF uses a mix of methods; both system expansion (i.e. the initial cycle is credited with the impact potentially avoided from e.g. reuse or recycling by substituting the most likely corresponding technology and/or practice in the subsequent use cycle) and 100:0, 0:100 and 50:50 allocation, depending on the market situation of the material (i.e., whether there is a high or low supply and demand) (ibid). However, in reuse situations, the CFF equally distributes the impacts between the cycles, regardless of the timing of the emissions (ibid).

Eleven different allocation approaches were assessed in the development of the CFF (Allacker et al., 2017). Among these were the more unconventional approach: the linear degressive (LD) approach, which enables distributing environmental impacts over an entire cascade of cycles appealing in terms of CE. LD uses a discounting principle where production and disposal impacts are linear-degressively allocated i.e. the highest share of impacts is allocated to the cycle where the impact happens. The 50:50 approach is used to allocate impacts from re-loop processes (e.g. reuse and recycling) equally between the first and subsequent use cycle of the material.

There is no single widely accepted allocation approach (Allacker et al., 2014) and different approaches are recommended for different products and loops (Schrijvers et al., 2016). However, different allocation approaches lead to different LCA results and conclusions and consequently to different choices of CE design strategies (Allacker et al., 2017; Cederstrand, Riise, & Uihlein, 2014; C. De Wolf et al., 2020). Use of different allocation approaches further hinders reliable comparisons between LCAs (C. De Wolf et al., 2020).

Existing allocation studies build on simplified short-lived products (Allacker et al., 2017; Van Der Harst, Potting, & Kroeze, 2016). Limited research exists on how the building sector's complex long-lived products, circular designed buildings and components perform under these approaches. Selecting and/or developing an allocation approach for CE in the construction sector requires testing of the allocation approaches on sector-specific products to deal with their inherent complexity in a suitable manner. Furthermore, existing allocation studies tend to focus on method development for single VRPs (e.g. reuse (C. De Wolf et al., 2020; Densley Tingley & Davison, 2012) or recycling (Niero & Olsen, 2016)) rather than a chain of multiple VRPs (e.g. a component that is reused, then recycled and finally recovered) in line with the CE concept.

2.4. SUMMARY OF STATE-OF-THE-ART

Although CE is a rapidly growing research field, and decades of preceding research fields exist behind the CE concept, the bulk of new building projects are not yet moving towards CE. In many ways, the complex institutional characteristics of the building sector do not support implementation of CE and therefore a tailored approach is needed. However, existing CE research within the building sector shows signs of fragmentation and lack a holistic perspective. This is evident from the lack of a common CE definition, narrow focus on single CE dimensions, diverging degrees of adoption, few partial/full-scale CE building cases, insufficient development of design and decision-making support, absent CE targets/metrics, and scarce environmental performance assessments of CE solutions. A comprehensive and structured overview of the CE practices introduced in the building sector and their environmental performance is not evident from the existing literature.

LCA is increasingly used to assess the environmental performance of buildings and can support implementation of CE in the building sector. However, the simplified methodological approaches required to encourage the use of LCA in industry practice contrast with the rigorous analysis needed to support the credibility of building LCA. Furthermore, LCA method discrepancies hinder common conclusions on effective CE strategies from the numerous existing building LCAs. To implement CE in the Danish building sector, a harmonized comparison of the origin of embodied environmental impacts in Danish building types is desirable.

Conventional LCA boundaries are too restricted (i.e. focusing on single life cycles) compared to the system perspective (i.e. multi-cycling aspect) of CE. Although different recommendations have been made in LCA standards and by different scholars, there is no commonly accepted approach for how to allocate benefits and burdens of shared components and materials between cycles that share them. It is recognized that the choice of allocation approaches influences the LCA results and consequently design decisions. Existing studies do not consider how conventional and circular buildings, components and materials perform under different allocation approaches and the design decisions they give rise to.

Some existing literature provides environmental design guidelines for buildings. However, these publications are limited in their practical application for a CE, as they build on conventional LCA and building design approaches, consider the over complex building level or limited material level, or focus on single environmental impact indicators and single CE strategies. Comprehensive environmental CE building design guidelines are needed in practice.

CHAPTER 3. METHOD

This chapter explains the choice of methods applied in work on the dissertation. Table 1 in Chapter 1 illustrates the relationship between the methods and each of the publications of the dissertation.

3.1. SYSTEMATIC LITERATURE REVIEW

The common aim of research syntheses and meta-analyses is to offer "…new knowledge by making explicit connections and tensions between individual study reports that were not visible before" (Harsh, 2011). Hence, reviewing publications is used as a research method throughout work on the dissertation to position the work within existing research. Review forms the theoretical background sections of Publications 2 and 3. However, a systematic literature review forms the entire basis of Publication 1 and is used as the foundation for the research synthesis of state-of-the-art design and construction strategies that are being applied in relation to CE within the building industry. The systematic literature review method described by de Almeida Biolchini, Mian, Natali, Conte, & Travassos (2007) was used as it ensures rigour and objectivity in the selected studies as well as replicability of the study, and it has been used by other recent CE studies (Pagoropoulos, Pigosso, & McAloone, 2017; Pieroni, McAloone, & Pigosso, 2019). The literature search for Publication 1 was conducted by carefully developing a review protocol consisting of three stages: data collection (including question formulation, source selection and studies selection), data analysis and finally data reporting (de Almeida Biolchini et al., 2007). As CE has been conceptualised within the last decade, the systematic literature review was not intended to be exhaustive (i.e. include preceding concepts) but rather it was to be a representation of state-of-the-art of strategies within the global building industry. Therefore, a very specific set of keywords related to CE, buildings and strategies was used. The literature search was conducted in Scopus, Web of Science and Google Scholar. The literature search was supplemented with backwards snowballing to capture additional literature of relevance (Wohlin, 2014). More detail on the search strategy can be found in Publication 1. The literature included a collection of 34 papers from 13 different countries from 2013-2019, consisting of both scientific and grey literature, as CE has to a large extent been developed in grey literature. Design and construction strategies that optimise buildings' emissions, resource use and/or waste generation in line with the CE concept were mapped, together with their fundamental characteristics, in a spreadsheet. The spreadsheet laid the foundation for grouping the strategies into a taxonomy of overarching design and construction strategies as well as their level of application and readiness.

3.2. CASE STUDIES

The case study is a comprehensive empirical research method that focuses on understanding a contemporary phenomenon within a specific, complex real-life setting (Yin, 2003). Case studies are ideal to address buildings' inherent unique, complex, dynamic and site-specific nature and are commonly used within environmental impact performance research on buildings (Ruuska, 2018). Case studies were used throughout the work on the PhD due to the context-specific focus of the PhD: 1) the geographical setting (i.e. Danish), 2) the inherent complexity of contemporary buildings and 3) CE building design and construction strategies. Case studies were used as an intensive quantitative analysis of a small number of cases, where the goal was to understand a larger class of similar cases (a population of cases).

Publication 2 is based on a comparative case study based on a selection of four case study buildings to quantify where the largest potential for impact reduction exists in contemporary buildings within a Danish context consisting predominantly of concrete structures. A 'random' selection of cases was chosen to achieve a representative sample of different Danish buildings that allows for generalization across the cases, although the sample was 'stratified' to represent selected subgroups of commonly constructed building types, i.e. a school, an office, a hospital and a residential building (Flyvbjerg, 2006). The specific building cases were selected based on their high detail of information about the buildings' material inventory and their temporal relevance (i.e. they were all built within the last 5 years). For Publication 3, the LCA outcome was compared from analysing four individual case examples of circular designed building components (i.e. a design for disassembly (DfD) concrete column and a timber column for direct reuse, recyclable roof felt and a DfD window with a reusable frame) using four different LCA allocation approaches. An 'extreme case' selection was chosen to achieve a representation of different CE design strategies (i.e. reuse and recycling) (ibid). 'Maximum variation' cases were used for Publication 4 to obtain information on the environmental performance of fundamentally different circular pathways (ibid). Hence, five different design variants of the same structure type were synthesised focusing on different VRPs (i.e. reduce, reuse, regenerate, refurbish, recycle and recover) for each variant. The variants consist of a resource-efficient, bio-based, DfD and adaptable variant that are compared to a corresponding conventional business-as-usual variant. The structural variants are not proven concepts, but ideas about 'ideal' circular solutions based on the most prevalent CE design and construction strategies identified in Publication 1, embodied GHG optimisation opportunities identified in Publication 2, plausible future scenarios, precedent and current circular building projects (Ellen MacArthur Foundation, 2016; Partners Circle House, 2018; van Stijn & Gruis, 2019), products (Lignatur, 2020) and circular design theories (Brand, 1994; Habraken, 1972). More detail on the case studies can be found in Publications 2-4.

3.3. LIFE CYCLE ASSESSMENT

In Publications 2-4, LCA is used to quantify the embodied environmental impact potentials of the cases presented in section 3.2. Case Studies. The following explains the harmonised LCA approach following the EN15978 standard for assessment of the environmental performance of buildings used in Publications 2-4. Details of the LCA modelling can be found in Publication 2-4.

3.3.1. PURPOSE OF ASSESSMENT

The studies in Publications 2-4 vary in their goal and intended use. The goal in Publication 2 is to identify and compare the embodied GHG emission hotspots of four different building typologies (i.e. a school, an office, a residential building and a hospital). The impact potentials are calculated using the 'cut-off' allocation approach used in the EN15978 and EN15804 standards. In Publication 3, the goal of the LCA is to test the effect of different existing allocation approaches on the embodied GHG emissions of four different circular building components (i.e. a design for disassembly concrete column and a timber column for direct reuse, recyclable roof felt and a window with a reusable frame). The results are calculated using two prevalent allocation approaches: EN15978/15804 cut-off and PEF's CFF, and two unconventional allocation approaches: 50:50 and LD based on the description from (Allacker et al., 2017). In Publication 4, the goal is to assess the environmental performance of fundamentally different circular pathways in order to derive design guidelines. The assessment is carried out on five different structural variants, each with their own circular strategy. The results are calculated using the allocation approach developed from Publication 3.

3.3.2. OBJECT OF ASSESSMENT

The functional unit varies between Publications 2-4 due to the differences in goal and scope. In Publication 2 the object of assessment is the four case buildings. Thus, the functional unit was set to *1m^2 of the building's gross floor area per year for a RSP of 100 years.* The RSP was set according to the Danish LCA practice (Aagaard, Brandt, Aggerholm, & Haugbølle, 2013; Green Building Council Denmark, 2020) which is very long compared to similar studies that use 50 years (Hossain & Ng, 2018; Marsh, 2017). In Publications 3 and 4, the focus of assessment is on the environmental impact potential of different circular building components within a system of cycles and how the cycling affects the individual cycles of that system. Hence, in Publication 3 the functional unit was set to *the use of the specific circular building component (i.e. a reusable concrete and timber column, recyclable roof felt and a window with a reusable frame) in a circular system (i.e. 3x80 years, 3x20 years and 2x25 years for the concrete and timber column, roof felt and window respectively).* In Publication 4, the functional unit was set to *the use of a specific circular tunnel structure with the dimensions of 3m high, 6m wide and 7.2m deep for multi-storey (+3 story) buildings for a period of 200* *years in a circular system.* To be able to compare the variants, the RSP (i.e. 200 years) was set according to the variant with the longest functional lifespan (i.e. the period of time during which the original function of the building component is needed, in this case a concrete structure (Aagaard et al., 2013)). Thus, the other variants with a shorter lifespan (e.g. 75 years) are placed 2.67 times within the 200 years. It should be noted, that the fractional placement deviates from the prescribed approach of the EN15804 standard in order to adapt to the purpose of CE. Furthermore, the 200 years deviates from the 120-year service life specified for concrete by Aagaard et al. (2013) according to the building's lifespan, however, concrete can have a much longer technical lifespan (i.e. the period of time during which the building component is technically and physically able to fulfil its original function (ibid)). Additionally, society may be forced to maintain buildings, components and materials much longer in the future than is currently the practice in light of the resource and climate challenge, and increase the functional spaces within existing stocks due to increasing land expansion challenges (Assefa & Ambler, 2017). Therefore, using a traditional lifespan is not sufficient to measure the potential benefits of long-lasting designs.

In Publication 2, the system boundaries include the following life cycle stages and modules stated in EN15978: production (A1-A3), replacements (B4), waste processing and disposal (C3-C4) based on the Danish approach (Birgisdottir & Nygaard Rasmussen, 2019), however also including reuse, recycling and recovery potential (D) relevant for CE. B4 usually includes both the production associated with material replacements, waste management and potential reuse, recycling and recovery. However, in Publication 2, B4 only includes the production of replacements and waste management and potential reuse, recycling and recovery of the replaced material are placed in C4–C3 and D respectively, in order to evaluate these separately. In Publications 3 and 4, the same modules (except for module D) are included, although for the entire chain of the assessed building components' cycles. Hence, all the use-, and life cycles of components, parts and materials inside, and outside of the system were assessed. Material cycles that happen outside of the components' life cycles were also considered. Operational energy (B6) of the case buildings in Publication 2 was not included, as only the material-related impact potentials are of interest. Service lives specified by Aagaard et al (2013) were used for individual building materials and components. EoL scenarios were set according to existing Danish waste treatment practices and secondary material markets (CLEAN, 2014; Danish EPA, 2017).

3.3.3. MATERIAL QUANTIFICATION

The inventory of the case buildings used in Publication 2 was compiled using building information models. Missing information was obtained from supplier information, estimation procedures and assumptions (e.g. technical datasheets and environmental product declarations (EPDs). In work on Publication 2, the inventory was mapped in detail, including all structural elements (load-bearing and non-loadbearing), coverings and finishing of all building elements (e.g. carpets, paint, plaster etc.) and technical installations (e.g. heaters, piping, ventilation units etc.). However, connectors (e.g. nails and screws) were not included. For Publication 3, the inventory was compiled using supplier information for the specific building component products used as cases. The inventory for the structural variants used in Publication 4 was assumed based in supplier information, example details and dimensioning rules-of-thumb. Only the ‘raw’ structure was considered; additional finishing was neglected.

3.3.4. ENVIRONMETNAL ASSESSMENT TOOL, DATA AND INDICATORS

In Publication 2, the four case buildings were modelled in LCAbyg v3.2, the Danish LCA tool for buildings (Birgisdottir & Rasmussen, 2019). LCAbyg is used for DGNB certifications in Denmark (K. Kanafani, Kjaer Zimmermann, Nygaard Rasmussen, & Birgisdóttir, 2019) and the voluntary sustainable building class in the Danish building code (Danish Transport and Construction Agency, 2020). LCAbyg uses generic environmental impact datasets from the German Ökobau 2016 database, which follows the current European standards (EN 15978, 2011). LCAbyg v3.2 does not include module D and therefore it has been manually added if available in the Ökobau datasets. As LCAbyg is based on a product and single life cycle perspective, applying the cut-off allocation approach, it cannot model the multi-cycling scope of Publications 3 and 4. To be able to model the extended system boundaries and calculate results using different allocation approaches, the openLCA v1.9.0 was used, as it provides flexible modelling options. Environmental impact datasets from the globally recognized Swiss Ecoinvent 3.4 APOS database were used. Allocation is usually integrated at material level within the datasets of the database used for the assessment. Thus, Ecoinvent 3.4 APOS uses an allocation principle in the background system. However, at the aggregated building level (the foreground system) the allocation is carried out by the individual assessor.

It should be noted that, even though the same characterisation factors are used in all cases, Ökobau datasets include the stored, biogenic CO_2 in wood products, whereas Ecoinvent datasets do not. This leads to a different modelling in Publication 2 compared to Publications 3 and 4. In addition, the same material may yield different environmental impact potential results from Ökobau compared to Ecoinvent (Rasmussen et al., 2019). However, the publications are individual and are not compared with each other.

In Publications 2, 3 and 4, the environmental impact categories are reported at midpoint level using characterisation factors from the Centre for Environmental Studies (CML) baseline as specified by EN 15804. The assessments in Publications 2 and 3 focus on assessing the embodied GHG emissions of the cases using the midpoint impact category global warming potential (GWP) to give an indication on the cases’ environmental performance. However, in development of the design guidelines in Publication 4, a more comprehensive assessment was conducted using 11 different environmental, resource use and toxicology midpoint impact categories were assessed besides GWP (ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP), eutrophication potential (EP), abiotic depletion potential for elements (ADPe), abiotic depletion potential for fossil resources (ADPf), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), human toxicity potential (HTP) and terrestrial ecotoxicity potential (TETP)). To identify the best performing variant, the variants are ranked based on their average percentage saving across all 11 impact categories as well as the material flow analysis (MFA) explained in section 3.4 using equal weighting compared to a corresponding conventional business-as-usual variant. Details on the development of the design guidelines can be found in Publication 4.

3.3.5. SENSITIVITY ANALYSIS

The sensitivity of a model portrays the degree to which variation of an input parameter or a modelling choice (e.g. allocation approach and time horizon in the functional unit) leads to variation of the LCA results (Hauschild et al., 2018). Thus, a sensitivity analysis helps identify key parameters and modelling choices that have a high influence on the results and thus informs on the robustness of the conclusions. Different sensitivity analysis approaches exist. For analysing parameter sensitivity, two approaches are generally used: ‘global sensitivity analysis’ considers how much each input parameter contributes to the output variance and ‘local sensitivity analysis’ investigates the effect of a certain change in input on the output by varying one parameter at a time (Rosenbaum, Georgiadis, & Fantke, 2018). ‘Scenario analysis’ can be used for evaluating the influence of modelling choices on the LCA results by assessing different possible scenarios (ibid).

Since multi-cycling far into the future as introduced in the cases used in Publications 3 and 4 is associated with a high level of uncertainty, the influence of parameters and modelling choices is of interest. Therefore, sensitivity analysis was applied as part of the interpretation to guide the development of the CE LD allocation approach in Publication 3 and the development of the design guidelines in Publication 4. In Publication 3, a local sensitivity analysis was used to determine a value for the allocation factor of the developed CE LD approach, which determines how the impacts of a system are divided between the cycles of that system. A value for the factor was determined by varying the allocation factor until a value was found for which the impact distribution stabilised itself. In Publication 4, a scenario-based sensitivity analysis was applied to assess the influence of the modelled lifespans and number of cycles on the structural variants’ environmental performance. Several ‘what-if’ scenarios that encompassed a ‘better’ or ‘worse’ case compared to the baseline scenario were assessed. The scenarios considered how a variant’s performance would change: 1) if the length of the variant’s use were shorter/longer than designed for, 2) if the length of the variant’s material cycles were longer/shorter than designed for, 3) if reuse/recycling cycles that the variant had been designed for were not realised in the future and 4) if more cycles than the variant was designed for occurred in the future. Details of the sensitivity analyses can be found in Publications 3 and 4.

3.4. MATERIAL FLOW ANALYSIS

Material flow analysis (MFA) is a method used to characterize and track material input/output flows and stocks (Heeren & Hellweg, 2019). MFA has been used to assess building material stock at national, regional and city levels (Heeren & Hellweg, 2019; Tingley & Arbabi, 2017). As resource efficiency is an important aspect of CE, MFA has recently been suggested for assessing CE to determine reuse, recycling and recovery potentials of stocks and to plan for future material demands (Giesekam & Pomponi, 2017; Tingley & Arbabi, 2017). MFA can thus be used in parallel with/to support the LCA (Pauliuk, 2018; Pomponi & Moncaster, 2017). Hence, MFA was used in Publication 4 to analyse the material flows of the structural variants to guide the development of the design guidelines together with the LCA. Different MFA modelling methods exist for different purposes (Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). In Publication 4, a simple ‘bottom-up’ approach accounting for the inventory of each variant was used (Tanikawa et al., 2015). Inputs (virgin, non-virgin, renewable and non-renewable), outputs (reusable, recyclable, recoverable/biodegradable and disposed) and material consumption (subtracting reusable/recyclable material from the import) were calculated for the primary cycle of the five structural variants.

3.5. EXPERT SESSIONS

Explorative, qualitative research approaches, such as expert interviews, are advantageous to use in research fields that are not yet well-established such as CE (Edmondson & Mcmanus, 2007). Expert interviews have been used in several recent CE studies (Densley Tingley, Cooper, & Cullen, 2017; Giesekam, Barrett, & Taylor, 2016; Kyrö, Jylhä, & Peltokorpi, 2019; Leising et al., 2018). For Publication 3 and 4, ten semi-structured expert sessions were conducted with 49 experts from academia, industry and government within the field of LCA and CE in the built environment. From the PhD’s industrial point of view, the expert sessions were used to evaluate and iteratively improve the practical use of the LCA allocation approach and design guidelines developed in Publication 3 and 4, respectively. The sessions focused on information concerning the validity and improvements of the developed LCA allocation approach and design guidelines. The experts’ answers and remarks were summarised, categorised and analysed from the session transcripts using an inductive coding technique (i.e. emergent coding) to quantify the content (Dahlsrud, 2008; Haney, Russel, Gulek, & Fierros, 1998; Kirchherr et al., 2017). See Publications 3 and 4 for further details on the expert sessions.

CHAPTER 4. FINDINGS

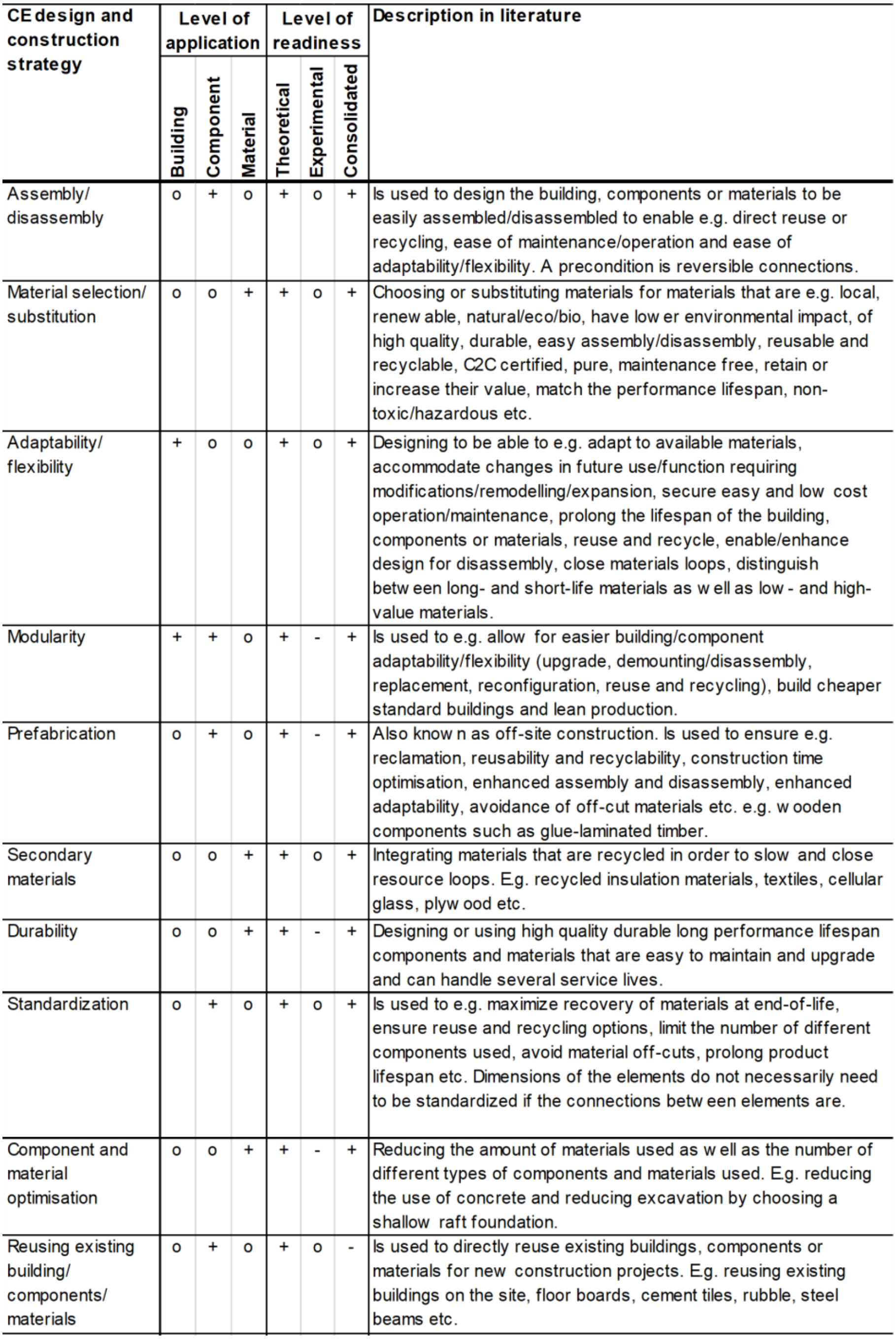
This chapter summarises and discusses the key findings of this dissertation, incorporating recent literature where available. The findings are presented according the four research questions of the four individual core publications for this dissertation, respectively.

4.1. WHICH DESIGN AND CONSTRUCTION STRATEGIES ARE BEING RELATED TO CE?

Publication 1 addresses the research gap presented in Chapter 1 about the lack of a commonly acknowledged CE definition in the building sector. Publication 1 systematically reviews and compares state-of-the-art design and construction strategies that are being applied in relation to the CE concept (i.e. reduces environmental impacts, resource consumption and/or waste) within the global building sector. With focus on essential shared practices, quality and characteristics, the identified strategies were grouped together into a taxonomy of sixteen overarching CE design and construction strategies. To achieve a deeper insight into each of the synthesised strategies' status within the building industry, several different types of information were extracted from the selected literature. Namely their popularity, level of application and readiness, and connections between the strategies. See Publication 1 for further details.

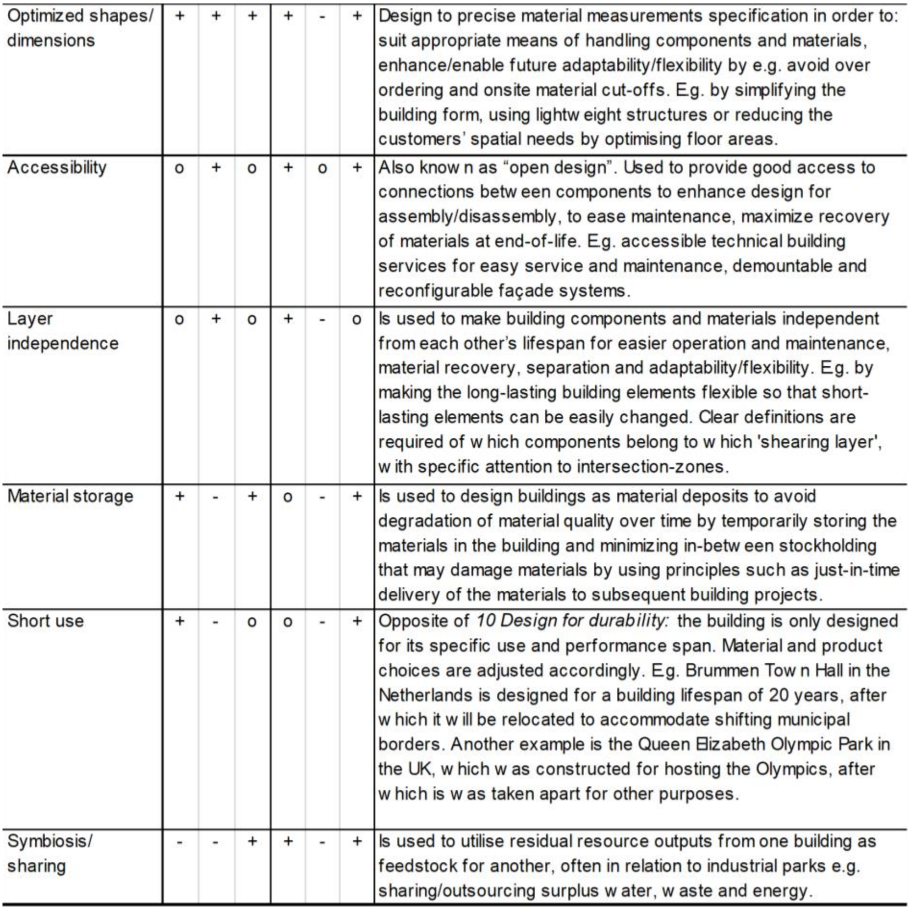
Table 2 shows an overview and description of the sixteen design and construction strategies ranked by number of occurrences. The description of each strategy reveals that they are interpreted and practised in different ways with different goals in the selected publications. The systematic literature review shows that the design strategies are predominantly applied as preventive strategies in the design stage, moving away from end-of-pipe waste management strategies such as recycling at EoL. The three most encountered strategies are: designing for assembly/disassembly, deliberate material selection/substitution and designing for adaptability/flexibility. The review indicates a predominant focus on the VRPs reuse, reduce and recycle (in that order). This includes integrating these VRPs into the design of present-day buildings and designing for them to potentially happen in the future. Most of the strategies are applied at both the overall building level as well as component and material level. However, assembly/disassembly, selection/substitution and adaptability/flexibility are more pronounced at the component, material and building level respectively. Furthermore, it has been suggested that some strategies are more suitable for some building, component and material types than others, as also suggested by (Assefa & Ambler, 2017; Densley Tingley & Davison, 2012). For example, prefabrication and modularity are ideal for residential buildings that often consist of a number of identical housing units (Partners Circle House, 2018).

Table 2. Taxonomy of CE building design and construction strategies. Adapted from Publication 1 (Eberhardt, Birkved, & Birgisdottir, 2020a).



CE design and construction strategy	**Level of application**			**Level of readiness**			**Description in literature**
	Building	**Component**	**Material**	**Theoretical**	**Experimental**	**Consolidated**	
Assembly/ disassembly	o	+	o	+	o	+	Is used to design the building, components or materials to be easily assembled/disassembled to enable e.g. direct reuse or recycling, ease of maintenance/operation and ease of adaptability/flexibility. A precondition is reversible connections.
Material selection/ substitution	o	o	+	+	o	+	Choosing or substituting materials for materials that are e.g. local, renew able, natural/eco/bio, have low er environmental impact, of high quality, durable, easy assembly/disassembly, reusable and recyclable, C2C certified, pure, maintenance free, retain or increase their value, match the performance lifespan, non-toxic/hazardous etc.
Adaptability/ flexibility	+	o	o	+	o	+	Designing to be able to e.g. adapt to available materials, accommodate changes in future use/function requiring modifications/remodelling/expansion, secure easy and low cost operation/maintenance, prolong the lifespan of the building, components or materials, reuse and recycle, enable/enhance design for disassembly, close materials loops, distinguish betw een long- and short-life materials as w ell as low - and high-value materials.
Modularity	+	+	o	+	-	+	Is used to e.g. allow for easier building/component adaptability/flexibility (upgrade, demounting/disassembly, replacement, reconfiguration, reuse and recycling), build cheaper standard buildings and lean production.
Prefabrication	o	+	o	+	-	+	Also know n as off-site construction. Is used to ensure e.g. reclamation, reusability and recyclability, construction time optimisation, enhanced assembly and disassembly, enhanced adaptability, avoidance of off-cut materials etc. e.g. w ooden components such as glue-laminated timber.
Secondary materials	o	o	+	+	o	+	Integrating materials that are recycled in order to slow and close resource loops. E.g. recycled insulation materials, textiles, cellular glass, plyw ood etc.
Durability	o	o	+	+	-	+	Designing or using high quality durable long performance lifespan components and materials that are easy to maintain and upgrade and can handle several service lives.
Standardization	o	+	o	+	o	+	Is used to e.g. maximize recovery of materials at end-of-life, ensure reuse and recycling options, limit the number of different components used, avoid material off-cuts, prolong product lifespan etc. Dimensions of the elements do not necessarily need to be standardized if the connections betw een elements are.
Component and material optimisation	o	o	+	+	-	+	Reducing the amount of materials used as w ell as the number of different types of components and materials used. E.g. reducing the use of concrete and reducing excavation by choosing a shallow raft foundation.
Reusing existing building/ components/ materials	o	+	o	+	o	-	Is used to directly reuse existing buildings, components or materials for new construction projects. E.g. reusing existing buildings on the site, floor boards, cement tiles, rubble, steel beams etc.

Table 2. continued



Optimized shapes/ dimensions	+	+	+	+	-	+	Design to precise material measurements specification in order to: suit appropriate means of handling components and materials, enhance/enable future adaptability/flexibility by e.g. avoid over ordering and onsite material cut-offs. E.g. by simplifying the building form, using lightweight structures or reducing the customers' spatial needs by optimising floor areas.
Accessibility	o	+	o	+	o	+	Also known as "open design". Used to provide good access to connections between components to enhance design for assembly/disassembly, to ease maintenance, maximize recovery of materials at end-of-life. E.g. accessible technical building services for easy service and maintenance, demountable and reconfigurable façade systems.
Layer independence	o	+	o	+	-	o	Is used to make building components and materials independent from each other's lifespan for easier operation and maintenance, material recovery, separation and adaptability/flexibility. E.g. by making the long-lasting building elements flexible so that short-lasting elements can be easily changed. Clear definitions are required of which components belong to which 'shearing layer', with specific attention to intersection-zones.
Material storage	+	-	+	o	-	+	Is used to design buildings as material deposits to avoid degradation of material quality over time by temporarily storing the materials in the building and minimizing in-between stockholding that may damage materials by using principles such as just-in-time delivery of the materials to subsequent building projects.
Short use	+	-	o	o	-	+	Opposite of *10 Design for durability:* the building is only designed for its specific use and performance span. Material and product choices are adjusted accordingly. E.g. Brummen Town Hall in the Netherlands is designed for a building lifespan of 20 years, after which it will be relocated to accommodate shifting municipal borders. Another example is the Queen Elizabeth Olympic Park in the UK, which was constructed for hosting the Olympics, after which is was taken apart for other purposes.
Symbiosis/ sharing	-	-	+	+	-	+	Is used to utilise residual resource outputs from one building as feedstock for another, often in relation to industrial parks e.g. sharing/outsourcing surplus water, waste and energy.

Note: Legend – Theoretical: theoretical research e.g. conceptual studies; Experimental: research with a practical application e.g. prototypes and test/pilot projects; Consolidated: applied in a 'real-life' building project. +: level in which the given strategy is most pronounced, -: level in which the strategy has also been mentioned, o: the strategy has not been represented within the given level.

Although the sixteen strategies are individual based on their practices, quality and characteristics, one strategy may aid one or more other strategies. For example, assembly/disassembly may enhance adaptability/flexibility. The strategies are believed to be related in ways that have not been recorded in Publication 1. The review suggests that a stronger link between research and practice is needed to progress CE, as developments are taking place in both research and industry, although independently of one another. Similarly, Reike et al. (2018) found that many academic contributions to CE are generally highly theoretical. The choice of design and construction strategies is often based on 'intuition' due to lack of knowledge about their environmental performance i.e. which strategies have the biggest potential of minimising buildings' environmental impacts. Only 8/34 studies quantified the chosen strategy's environmental performance. The taxonomy in Publication 1 creates a basis for structuring and prioritising the strategies according to their environmental-impact minimisation potential in Publication 4 to support design and decision-making.

4.2. WHICH LIFE CYCLE STAGES, BUILDING COMPONENTS AND MATERIALS INDUCE THE LARGEST ENVIRONMENTAL IMPACT POTENTIALS WITHIN PREVAILING DANISH BUILDING TYPES?

Publication 2 assesses and compares the embodied GHG emissions hot spots of four conventional Danish buildings (a school, an office, a residential building and a hospital) and points towards CE strategies and the strategies' potential emissions savings for the four buildings. The buildings were assessed following the harmonised Danish LCA method valid at the time of modelling using the national tool LCAbyg v3.2 and a RSP of 100 years. The school building consists of five storeys with a concrete and steel structure with aluminium facades. The office building consists of a four-storey concrete and steel structure with aluminium curtain walls. The hospital building has a four-storey concrete structure with brick and glass facades. The residential building consists of four concrete buildings of different heights (up to six storeys) with brick facades. See Publication 2 for further details.

Figure 3 shows the embodied GHG emissions profiles associated with the life cycle stages, components and materials of the hospital building. See Publication 4 for details on the profile of the school, office and residential building. The buildings' embodied GHG emissions profiles show both similarities and differences between the buildings. In line with previous research (Anand & Amor, 2017), production is by far the primary contributor to the buildings' embodied GHG emissions, with 58%-68%. Hence, reducing current emissions is crucial. Avoiding or postponing production of new buildings by reusing existing buildings is the ultimate solution. For example, reuse of the concrete structure could yield a 31% saving of the hospital's embodied GHG emissions. Similarly, long-lasting designs should be considered to avoid premature obsolescence of buildings that are built today.

Component and material replacements during building operation account for 11%-27% of the buildings' total embodied GHG emissions. Some of these emissions take place before the climate targets for 2030 and 2050. Thus, reducing the emissions from production and disposal associated with replacements as well as the frequency of replacements is important. For example, substituting the aluminium curtain walls (one replacement over 100 years) and carpets (five replacements over 100 years) with wood can save 16% of the office building's total embodied GHG emissions.

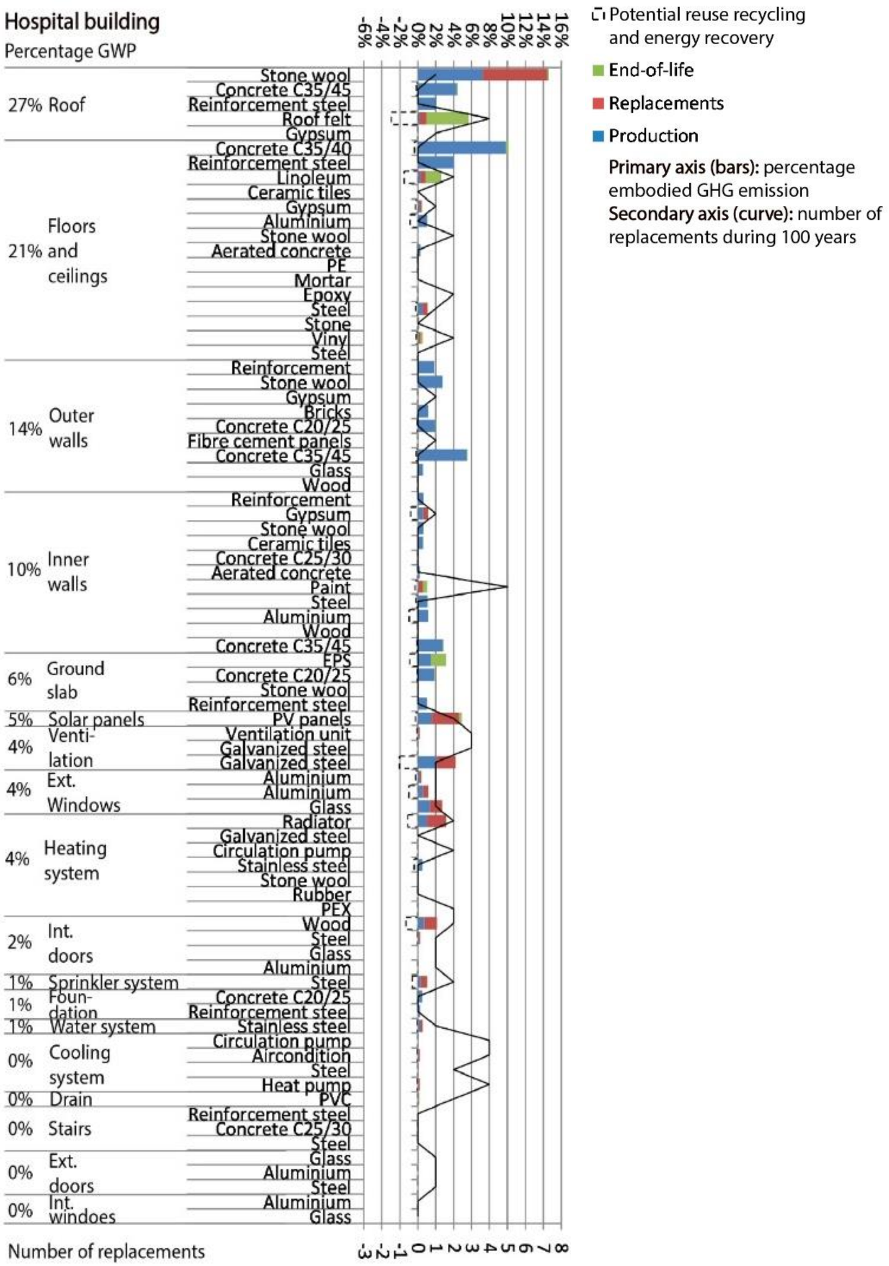


Figure 3. Embodied greenhouse gas emissions profile of the hospital building. From Publication 2 (Eberhardt, Rønholt, Birgisdottir, & Birkved, 2020b).

13%-21% of the buildings' total embodied GHG emissions come from the EoL stage. A large reuse, recycling and recovery potential is available at the components' and materials' EoL, showing as a negative value and indicating a potential saving ranging between 16%-34% of the buildings' total embodied GHG emissions. For example, recycling the frequently replaced roof felt instead of incineration at EoL could yield a 5% and 9% reduction in the hospital and residential buildings' embodied GHG emissions, respectively. CE initiatives should not neglect facilitating these future potentials, for example through DfD. However, these potentials are associated with notable uncertainty, as they are only gained when and if they happen at the components' and materials' EoL sometime in the future. However, the uncertainty of these potentials can be reduced by taking measures to enhance future reuse, recycling and recovery through, for example, DfD thereby minimising future emissions. For example, reuse of the prefabricated floors, columns and beams at the office building's EoL would yield a 16% saving of the office building's total embodied GHG emissions.

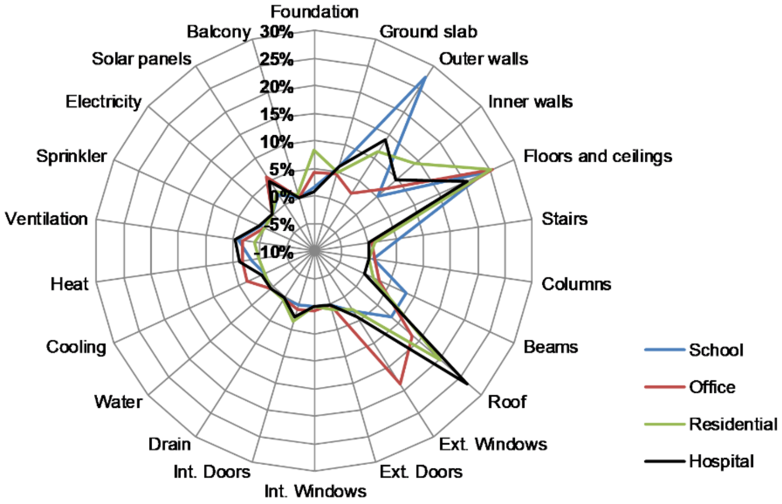


Figure 4. Percentage embodied greenhouse gas emissions of the building components of the school, office, residential and hospital buildings. Note module D is not included. Adapted from Publication 2 (Eberhardt et al., 2020b)

Figure 4 shows the percentage embodied greenhouse gas emissions stemming from the building components of the assessed buildings. The component groups with the highest contribution to the buildings' embodied GHG emissions all belong to the structure. The floors and ceilings contribute 21%-26% of the buildings' embodied GHG emissions, primarily stemming from the production of concrete. The outer walls contribute 12%-27% of the buildings' embodied GHG emissions, stemming from the use of different embodied GHG-emissions-intensive materials. The production and replacement (once over 100 years) of aluminium in particular accounts for 24% of the school's total embodied GHG emissions, although it only makes up 1% of the total building mass. Use of recycled aluminium or the use of wood achieves a 19% and a

24% reduction respectively of the school building's total embodied GHG emissions. Hence, correct selection of materials is vital to reduce production-related embodied GHG emissions. The roof accounts for 8%-27% of the buildings' total embodied GHG emissions stemming from frequent replacement and disposal (five times over 100 years) of roof felt as well as production, replacement (once over 100 years) and disposal of expanded polystyrene insulation and mineral wool. The inner walls contribute 7%-14% of the total embodied GHG emissions of the office, residential building and hospital building. Although the contribution is most pronounced for concrete, the remaining contribution originates from a combination of several other materials in the inner walls. In this case, component redesign should be considered rather than sub-optimisation of individual materials. When accumulated, some material groups account for a high percentage of the buildings' total embodied GHG emissions (e.g. concrete accounts for 27% of the school's total embodied GHG emissions). Such gross summations are often seen in building LCAs, but they are not very helpful from an optimization perspective, as it is easy to overlook that the concrete is used in different functions/applications/areas of the buildings, as seen in Figure 3. Hence, substituting concrete altogether may prove difficult.

Identifying feasible emissions reduction opportunities depends on the interconnectedness between the building and its components and materials. Similarly, the environmental performance of buildings depends to a large extent on the use-context of the buildings, their components and materials. The findings suggest that the specific building type is less relevant in terms of the origin of the embodied GHG emissions than the fact that the buildings use similar building components and structures.

The results of Publication 2 show that initiatives going across and beyond the entire life cycle of the buildings, components and materials are needed to reduce current and future emissions to help achieve climate goals, as also suggested by others (Malmqvist et al., 2018; Pomponi & Moncaster, 2016). A combination of the handful of above-mentioned initiatives would yield significant emissions reductions over the buildings' life cycle (24%, 36%, 35% and 14% for the school, office, hospital and residential building respectively). Table 3 summarises the optimisation scenarios and their potential embodied GHG emissions reductions for each building.

As each building is unique, generalised learnings can be used in parallel with LCA to identify optimal reduction strategies for each building in question. For the same reason, the optimal CE strategies and how much reduction can be obtained may vary from building to building. Implementing detailed LCA modelling as performed in Publication 2 in the design phase, where building information is lacking (i.e. dividing the building into its inherent components and materials), would require practice-oriented LCA developments. Furthermore, the findings of Publication 2 should be perceived in light of the limited number of cases (four Danish concrete buildings). Thus, the results may only apply to these case buildings. Other developments are ongoing on larger samples of buildings to draw statistical conclusions on embodied emissions (Resch & Andresen, 2018)

Table 3. Optimisation scenarios and reduction potential of the buildings' total embodied GHG emissions.

Building	Optimisation	Reduction potential [%]
School	Substituting virgin aluminium façade plates and lamellas with secondary aluminium produced using hydro energy in Norway	19%
	Substituting virgin aluminium plates and lamellas on the facades with wood	24%
Office	Substituting the aluminium curtain walls with timber curtain walls	10%
	Design for disassembly of the prefabricated concrete elements (i.e. floor slabs, columns and beams) for reuse at the building's end-of-life	16%
	Substituting the carpets with wood floors	6%
Hospital	Recycling roof felt instead of incineration at end of life	5%
	Reuse of the concrete structure compared to complete demolition and new construction	31%
Residential	Recycling roof felt instead of incineration at end of life	9%
	Lean design of concrete elements (i.e. avoiding over-dimension) can yield approximately 18 kg CO_2 reduction per m^2 building	5%

4.3. HOW DO DIFFERENT ALLOCATION APPROACHES AFFECT THE LCA OUTCOME AND THE INCENTIVE FOR CE?

Allocation is applied in LCA to divide environmental impact potentials of shared products and materials between the different systems that share them, when the systems are assessed separately. Publication 3 explores how different allocation approaches allocate emissions between the different use cycles and life cycles of four circular building-component cases and the incentive that the allocation creates for CE. The two VRPs reuse and recycle are frequently applied in CE. Therefore, these VRPs form the basis of the four circular building-component cases assessed. The cases consist of a DfD concrete column and a timber column for direct reuse with three use cycles, recyclable roof felt with three use cycles and a DfD window with a reusable frame with two use cycles (see Figure 5). The embodied GHG emissions are divided between the use cycles and life cycles of the cases using two prevalent allocation approaches: EN15978/15804 cut-off and PEF's CFF, and two unconventional allocation approaches: 50:50 and LD. See Publication 3 for further details.

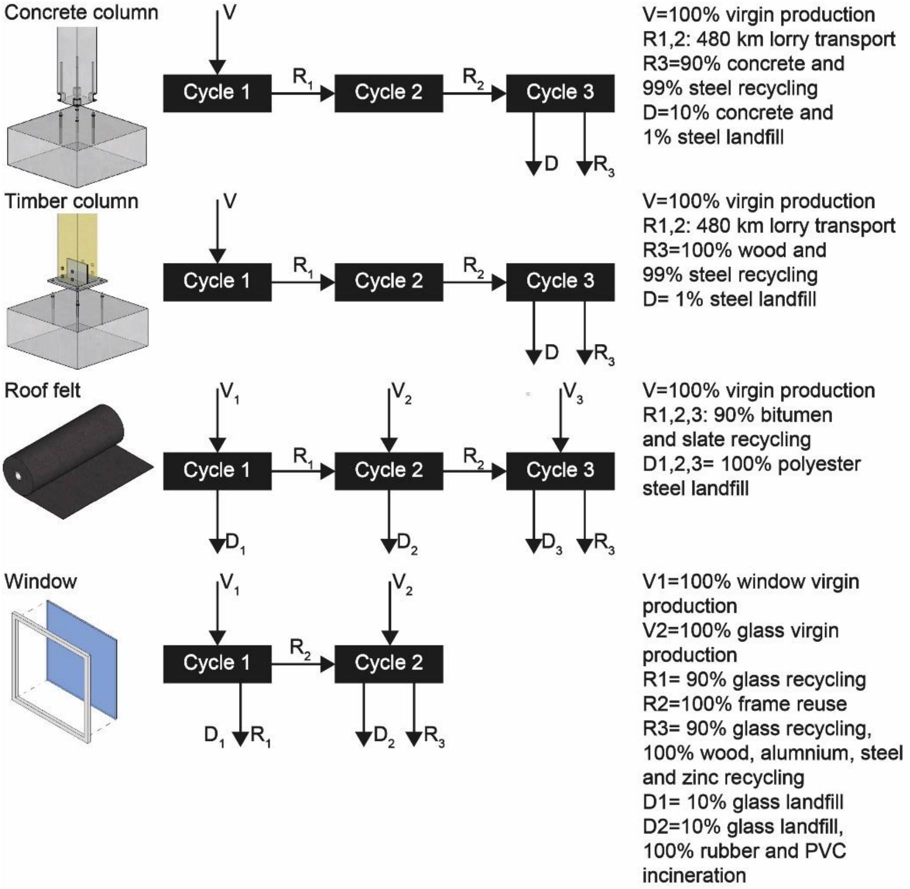


Figure 5. Flow diagram and processes of the concrete column, timber column, roof felt and window. Adapted from Publication 3 (Eberhardt, van Stijn, Nygaard Rasmussen, Birkved, & Birgisdottir, 2020c)

4.3.1. ALLOCATING IMPACTS BETWEEN DIFFERENT LIFE CYCLES

Figure 6 shows the emissions distribution between the different use cycles and life cycles of each of the assessed cases using the four different allocation approaches. Publication 2 highlights the apparent need to reduce both current and future impacts from buildings to help reach climate targets. With this in mind, notable distribution differences between the allocation approaches shown in Figure 6 indicate that different CE principles are promoted (i.e. narrowing, slowing and closing loops).

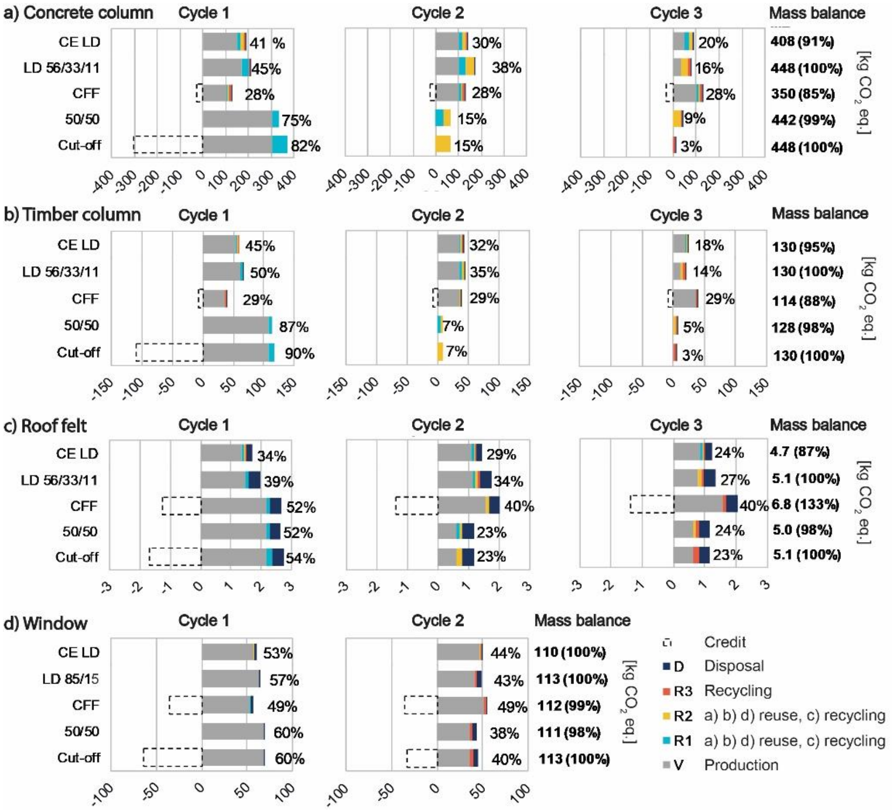


Figure 6. Embodied GHG emissions distribution between the cycles of the four cases applying different allocation approaches. Absolute emissions on the x-axis and percentage emissions stated at each bar. Mass balance is stated at the right side of the graphs in absolute and percentage emissions. Adapted from Publication 3 (Eberhardt et al., 2020c)

All the approaches incentivise narrowing loops as efficient resource use will lead to up-front emissions reductions for all the approaches. The EN15978/15804 cut-off approach and 50:50 approach allocate a very large share of the emissions to the first cycle, creating a great incentive for using secondary components and materials as the subsequent cycles receive far fewer emissions in comparison. This is especially seen for the EN15978/15804 cut-off approach, as both the emissions from virgin material production and the reuse or recycling emissions are ascribed to the first cycle. Hence, the second cycle receives the components or materials practically burden-free. Thus, DfD of the columns and window does not realise an emissions benefit in the first cycle. In other words, focus is created on lowering current emissions (i.e. narrow, slow and close loops today) rather than crediting current cycles for (potential) future savings (i.e. narrow, slow and close loops in the future). Other studies have found similar results (Densley Tingley & Davison, 2012; F. N. Rasmussen et al., 2019). A similar incentive is seen for the CFF of the roof felt, although this is less pronounced. Suggestions have been made to view building clients as carbon investors and attribute fewer emissions to the first cycle to encourage DfD as products with high embodied carbon are likely to have a higher value in the future due to likely carbon taxes to reduce emissions (Densley Tingley & Davison, 2012).

The EN15978/15804 cut-off approach does try to incentivise designing for narrowing, slowing and closing loops in the future by crediting cycles that send virgin material to reuse, recycling and/or energy recovery (seen as negative emissions), but not for sending secondary materials to reuse, recycling and/or energy recovery. For example, the window receives a credit for sending virgin glass to recycling in both cycle 1 and 2. However, this is limited to thinking only one cycle ahead and does not promote keeping materials cycled at their highest utility and value for as long as possible in line with the CE concept. It also highlights one of the crucial differences between the product perspective of the European standards and the larger system perspective of CE. The burden-free aspect of secondary materials can create a misguided incentive and demand for secondary material use. This is because the initial and potentially burdensome production of the material is ‘forgotten’ in the second cycle, contradicting the multiple life cycle considerations of CE. Additionally, there is a risk of double crediting if the crediting is not kept track of between the use cycles, due to the long time aspect of each cycle. For example, in the case where the first cycle receives a credit for sending the column to reuse and the second cycle receives the column burden-free. It is widely discussed among researchers how to interpret and use module D (Anderson, Ronning, & Moncaster, 2019; Delem & Wastiels, 2019) and guidance on how to avoid double-crediting is very unclear (EN 15804, 2013).

The CFF only credits recycling (i.e. the roof felt), whereas reuse is credited by equally sharing the emissions between the cycles (i.e. the concrete and timber columns, and window). Thereby, a great environmental advantage is created for DfD in the first cycle. However, reuse in the subsequent cycles becomes less advantageous compared to the cut-off and 50:50 approach. Compared to the other approaches, the CFF approach is more comprehensive but also more difficult to interpret and practice. It is left up the assessor to produce a reasonable assumption for some of the parameters of the CFF. Thus, it is difficult to ensure a harmonised application of the CFF. Furthermore, the CFF tries to incorporate a system perspective but the CFF was developed for assessing single products like the EN15978/15804 cut-off approach.

The LD approach considers the entire cascade of cycles. By doing so, it also implicitly takes into account the material quality. The LD approach allocates slightly fewer emissions to the first cycle and slightly more emissions to the subsequent cycles compared to the other approaches. Thereby, a sense of “shared” responsibility is created between the cycles while still providing a benefit of both DfD in the first cycle and reuse in subsequent cycles, although not as pronounced as for the other approaches. The 50:50 approach, and especially the CFF, does not comply with the mass balance of the assessed cases compared to the cut-off approach and LD approach. This is because the 50:50 approach allocates emissions from recycling at

EoL in the last cycle outside of the system. For the CFF it is caused by the quality correction of the emissions (M. Wolf & Chomkhamsri, 2014). High uncertainty is related to the 50:50, LD and CFF, as emissions that happen today are allocated to cycles far into the future that may not occur. Hence, emissions may eventually be unaccounted for and could lead to greenwashing. Similarly, the LD can be misused by adding cycles that do not exist, thereby lowering the emissions per use cycle. However, the LD approach to some extent deals with the uncertainty because emissions are allocated according to when they happen in the system. On the other hand, it can be difficult to qualitatively estimate number of cycles within a long time aspect of building components and materials.

The results suggest that none of the approaches are objective, as they all seem to be based on value choices suggesting that some approaches seem more suitable in certain contexts and/or for reaching specific goals. For example, the EN15978/15804 values reducing current emissions. There are advantages and disadvantages of all the approaches. However, the LD approach is very appealing for environmental performance assessment of both open-loops and closed-loops within a closed loop supply chain (such as the ones assessed) in a CE in the built environment. It considers the number of cycles, it is simpler to use than the CFF, it creates an incentive for narrowing slowing and losing loops to reduce (now and to design for these in the future) in line with the findings of Publication 2, it deals with the uncertainty, and it implicitly considers the material quality from the number of estimated cycles.

4.3.2. DEVELOPING A CE LCA ALLOCATION APPROACH

Very little information is available on the LD approach and the LD approach has not yet been integrated in existing standards, but it has been discussed by other researchers (Allacker et al., 2017; C. De Wolf et al., 2020). The work in Publication 3 builds on the description and example of the approach given by Allacker et al. (2017). No insight is offered into the background of the approach, for example, which values choices form the basis for the distribution of impacts. To enhance the applicability of the LD approach in a CE setting in the building sector, and to create an incentive for CE in the building sector, the work in Publication 3 further develops the approach by determining how much of the impact should be allocated between the cycles of a cascading system to stimulate CE. The developed approach is called CE LD.

A number of factors can be used to determine how to share impacts between cycles such as the number of cycles, the uncertainty of the cycles, the length of the cycles, the material quality degradation over cycles, etc. The impact distribution in the CFF is determined by a multitude of different parameters, and this makes it very complex to use. To enhance applicability, an equation was developed that linear-degressively distributes the highest share of the environmental impacts from production and disposal to the cycle were the impact happens and linear-degressively shares the rest of the impact between the remaining cycles of the system. The equation is dependent on only two parameters: the ‘number of cycles’ and a factor ‘F’ (see Publication 4). ‘F’ determines the share of impacts allocated to the first cycle compared to the last according to when the impacts happen. ‘Number of cycles’ is chosen because CE emphasises life extension. Thus, the number of use cycles in the future should influence design decisions today. What constitutes a ‘fair’ value for the factor ‘F’ is questionable. However, ‘F’ was set to 50 as a sensitivity analysis showed that the impact distribution of the concrete column, roof felt and window stabilised itself the closer ‘F’ gets to 50.

The LD approach uses the 50:50 allocation approach to allocate impacts from re-loop processes (e.g. reuse and recycling) equally between the first and subsequent use cycle of the component or material. However, others suggest equally sharing the environmental impacts between the predicted cycles is more appropriate, especially for reuse (Densley Tingley & Davison, 2012; Eberhardt, Birgisdóttir, & Birkved, 2018a). Therefore, environmental impacts of re-loop processes of components and materials that are shared between more than one cycle are divided equally between the cycles that share them. The CE LD approach considers incineration as a re-loop and a life cycle instead of disposal, as energy is recovered giving the material one final use. Otherwise, the cycle receiving the material only to incinerate it becomes burden-free. In this way, it may motivate finding other alternative and more environmentally beneficial uses of the material. As the impacts from incineration are shared equally between the cycles it may also motivate the initial cycles to make early design choices to avoid incineration later on. In contrast, landfilling is not counted as a use cycle, as the material will have no further use at this point and the associated impacts are predominantly allocated to the cycle that landfills the material. It is challenging to determine the number for cycles for highly recyclable materials such as metals. Therefore, a default value of 10 cycles is assumed. This gives the metal an environmental advantage over other less recyclable materials and encourages the use of recyclable materials. For other materials, such as chipboard that can be recycled into new chipboards a number of times before final disposal, only one cycle is counted as it is too uncertain how many times it will be recycled. However, such assumptions may be changed if the cycles can be guaranteed in the supply chain. The CE LD approach takes into account that, in a CE, building components and materials (potentially) have multiple cycles that happen outside of the assessed building. However, the total impacts of the entire system, including the building and component and material cycles outside of the building, always add up to 100%.

In Figure 6, the developed CE LD approach is compared with the other allocation approaches assessed. The approach can be said to divide burdens in a ‘fairer’ way because all the cycles (stakeholders) share the benefit as well as the responsibility for the environmental impacts. Consequently, incentives are created to narrow, slow and close cycles today but also design for this in the future. However, it should be stressed that the LD approach and the CE LD approach developed need to be validated, as for the time being they are theoretical developments, in light of the lack of empirical data on the two approaches. Other important parameters for CE may have been overlooked, for example the CE LD approach does not take into account the length of cycles or that different cycles may have different lengths.

4.4. WHICH CE DESIGN AND CONSTRUCTION STRATEGIES RESULT IN THE LARGEST ENVIRONMENTAL IMPACT SAVINGS?

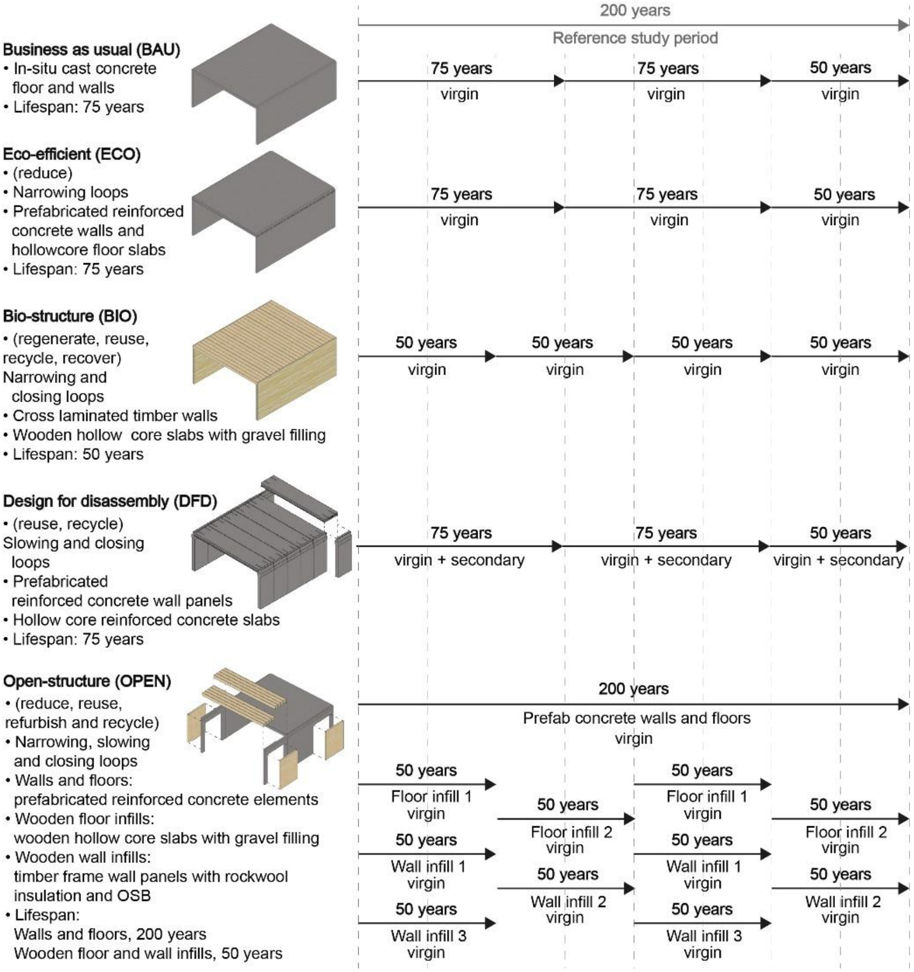


Figure 7. Circular concepts and lifespans of the baseline scenarios of the five structural design variants of the tunnel structure (3m high, 6m wide and 7.2m deep for +3 storey buildings). From Publication 4 (Eberhardt, van Stijn, Stranddorf, Birkved, & Birgisdóttir, 2020d)

Publication 4 explores the environmental benefits of different CE design and construction strategies. Environmental design guidelines are derived from applying selected CE design and construction strategies from Publication 1 and the developed CE LD approach from Publication 3 to five variants of a tunnel structure. The building structure is used as a case, as Publication 2 showed that the embodied GHG emissions of the four assessed buildings are related to many components of a building's structure. Four of the variants are based on circular design principles: 1) a resource efficient (ECO) version saving 22% concrete and 25% reinforcement, 2) a timber structure (BIO) where the glued laminated timber walls are reused once before being recycled followed by incineration for energy recovery with the hollow core timber floor slabs at the structure's EoL after 50 years, 3) a DfD concrete structure (DFD) with a lifespan of 75 years that uses a mix of reusable virgin and secondary elements, and 4) a lean concrete structure with openings (OPEN) in which insulated timber panels are placed or removed every 50 years to combine or separate adjacent floors and rooms to adapt to temporal user patterns, thereby prolonging the structures life to 200 years. The four circular variants are compared to a corresponding conventional variant: a business-as-usual (BAU) concrete structure that is down-cycled at the EOL after 75 years according to the current practice. Figure 7 shows the concepts of each of the five variants. A RSP of 200 years is used. Following the concept of CE, the variants are designed as a composite of components, parts and materials which – potentially - have different and multiple use and life cycles (see the flow diagrams in Figure 8). Nineteen different scenarios of the variants explore how the variants would perform under different future circumstances beyond what they were designed for, for example shorter/longer use, shorter/longer material cycles, unrealised reuse/recycling cycles and extra reuse cycles. Table 4 gives an overview of the assessed variants and scenarios and their applied circular design principles. To compare the variants' and scenarios' overall environmental performance, they are ranked from 1-24 (from the best to worst performance) based on their average percentage saving compared to the BAU of: 1) the LCA (all 11 impact categories) and MFA results, and 2) the GWP and MFA results (see Table 4).

For all the variants, the environmental performance primarily originates from material production, as was also found for the four buildings in Publication 2. Of the five variants, the OPEN results in the best overall performance with a rank of 4 in both rankings. The optimized performance is a result of the structure's design. The weight-heavy and impact-intensive concrete from the BAU has partially been substituted with light-weight and low-impact timber. The opening in the concrete structure facilitates easier adaptations, potentially prolonging the use of the structure. Both the DFD and OPEN structures explore the possibilities of utilizing the long technical lifespan of concrete through life-extending design solutions to prolong the functional lifespan. The DFD also uses a mix of primary and secondary concrete elements. However, the DFD does not match the performance of the OPEN structure with a rank of 15 based on the LCA and MFA and 13 based on the GWP and MFA. Therefore, it cannot be claimed that life-prolonging design implies a universal gain in all cases.

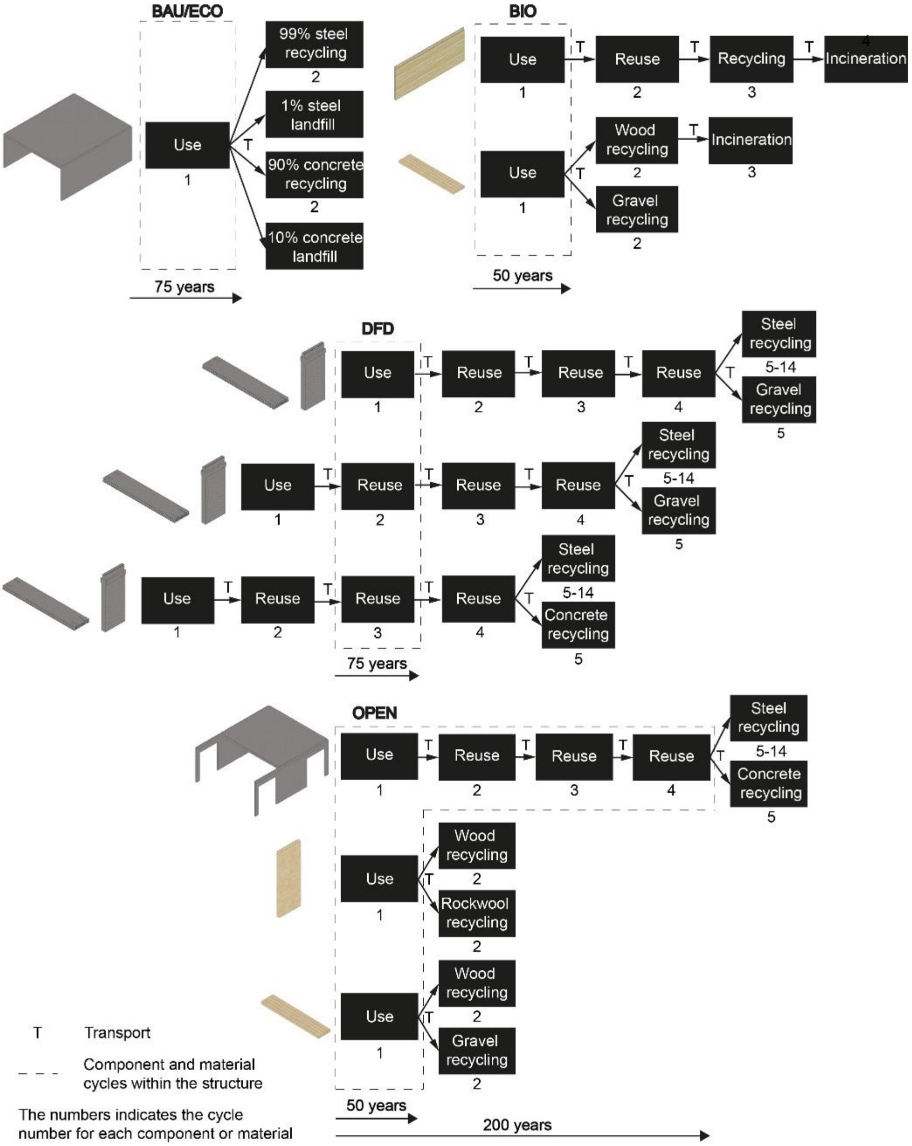


Figure 8. Flow diagrams of the structural variants. From Publication 4 (Eberhardt et al., 2020d)

Table 4. Ranking of the variants and scenarios and their applied design principles. Adapted from Publication 4 (Eberhardt et al., 2020d).

Ranking		**Variant/ scenario**	**Applied desing principle(s)**
LCA (all impacts) + MFA	**LCA (GWP) + MFA**		
1	1	BIO L200	Biomaterials, multiple cycles (reuse, recycle, recover), very long lifespan (200 years)
2	2	OPEN C+1	Adaptable (50 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), very long lifespan (200 years for the concrete structure), 1 additional cycle (reuse)
3	3	OPEN L200_75	Adaptable (75 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), very long lifespan (200 years for the concrete structure)
4	4	OPEN	Adaptable (50 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), very long lifespan (200 years for the concrete structure)
5	5	OPEN L200_25	Adaptable (25 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), very long lifespan (200 years for the concrete structure)
6	8	DFD L200	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle), very long long lifespan (200 years)
7	12	ECO L200	Lean design, long lifespan (200 years)
8	9	OPEN L75_25	Adaptable (25 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), long lifespan (75 years for the concrete structure)
9	14	ECO C+1	Lean design, 1 additional cycle (reuse)
10	10	OPEN L75_50	Adaptable (59 years between adaptations), durable materials, standard sized parts, multiple cycles (reuse, recycling), long lifespan (75 years for the concrete structure)
11	6	BIO C+1	Biomaterials, multiple cycles (reuse, recycle, recover), 1 additional cycle (reuse)
12	16	BAU L200	Linear design, very long lifespan (200 year)
13	11	DFD C+1	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle), 1 additional cycle (reuse)
14	18	BAU C+1	Linear design + 1 additional cycle (reuse)
15	13	DFD	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle),
16	7	BIO	Biomaterials, multiple cycles (reuse, recycle, recover), long lifespan (50 years)
17	15	DFD C-1	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle), 1 less cycle (reuse)
18	17	DFD C-2	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle), 2 less cycles (reuse)
19	20	ECO	Lean design, long lifespan (75 years)
20	21	BAU	Linear design, long lifespan (75years)
21	19	BIO L25	Biomaterials, multiple cycles (reuse, recycle, recover), short lifepan (25 years)
22	22	DFD L25	Standard sized parts, durable materials, demountable parts, reusable parts, multiple cycles (reuse, recycle), short lifespan (25 years)
23	23	ECO L25	Lean design, short lifespan (25 years)
24	24	BAU L25	Linear design, short lifespan (25 years)

In the case with the OPEN structure, the material design is equally as important as the life-prolonging design solution for the optimised performance. Furthermore, life prolongation can be achieved through a variety of different design solutions besides open design and DfD. Optimising the BAU using a leaner design (ECO) only provides a limited optimisation potential as it still builds on the business-as-usual practice.

Altering the number of cycles of the variants (e.g. adding or removing a reuse cycle) affects the variant's LCA performance in terms of the share of impact potentials distributed between the cycles. It also affects the MFA in terms of what happens to the materials after they leave the structure. An additional reuse cycle (C+1) results in an improved ranking of all the variants, as more material is sent to reuse and the environmental impact potentials are shared between more cycles and vice versa. Altering the lifespan of the variants (e.g. a longer or shorter use) affects the amount of material of the variants due to increased or decreased replacements within the 200-year RSP as well as the material origin, as a longer lifespan requires the use of virgin materials to ensure durability, thereby affecting both the LCA and MFA performance. Extending the lifespan to 200 years (L200) of the variants BAU, ECO, BIO and DFD significantly improves their ranking, as the variants are only produced once in 200 years, thereby decreasing the amount of material. For the OPEN variant, fewer adaptations (L200_75) lead to an improved ranking, while more adaptations (L200_25) degrades the ranking. Reducing the OPEN variant's functional lifespan from 200 years to 75 years with adaptions every 25 years and 50 years significantly worsens the variant's ranking. Despite a reduced functional lifespan, the OPEN variant still ranks better than any of the other variants. The only scenario that surpasses the performance of the OPEN is the BIO L200 with a prolonged lifespan of 200 years. Shortening the functional lifespan from 75 years to 25 years (L25) increases the number of replacements of the variants and amount of material proportionally, thereby worsening the ranking of the BAU, ECO and DFD. Publication 4 highlights how different scenarios in some cases affect the performance of the variants profoundly. The scenarios show that the variants are in general more sensitive to changes in lifespan (especially a shorter lifespan) compared to the number of cycles.

Table 4 shows that combining multiple circular design principles leads to a better performance than focusing on single circular design principles. For example, the highest-ranking scenario, BIO L200, combines biomaterials with multiple VRPs (reuse, recycling and recovery) and long use. Hence, optimising the environmental impact and material consumption is a matter of combining the right design principles and parameters (i.e. VRPs, lifespans and material types). However, this requires co-designing with all stakeholders in the supply chain to determine, realise and guarantee the circularity.

Publication 4 highlights the crucial difference between single-indicator assessments and multi-indicator assessments. Due to differences between the variants' and scenarios' average performance across all 11 impact categories compared with their performance in GWP, the two ranking methods result in different rankings for some of the variants and scenarios, for example DFD and ECO L200. Thus, the different ranking methods lead to different results and conclusions that affect design and decision making. The current industry focus on GWP does not necessarily lead to the best overall environmental performance, as other important impact categories are neglected. For example, transportation of the DFD's elements for reuse results in higher impacts in ODP, ADPe, ADPf and HTP compared to the BAU. However, these impacts are very uncertain, as the transportation does not occur until the structure's EoL after 75 years. Due to impacts related to forestry and harvesting, the BIO variant has a higher impact in ODP, POCP, EP and ADPe than the BAU. Only the ECO and OPEN variant yield savings in all 11 environmental impact categories compared to the BAU. Other ranking methods exist (e.g. normalization (Hauschild et al., 2018) and eco-cost (Vogtländer et al., 2010)) and there is no consensus on which to use. The choice of ranking method should thus be carefully considered, as it steers the CE direction for the sector and ultimately determines which way society will go. Thus, although the ranking of the variants and scenarios in Publication 4 can provide a simpler decision basis in the early design stage, it does not always represent the variants' and scenarios' performance within single indicators. See Publication 4 for further detail about the performance of variants and scenarios within individual impact categories.

Figure 9 shows the accumulated GWP performance of the variants over the 200-year RSP. Figure 9 highlights how the variants' environmental impact performance depends on the chosen time frame for the assessment. The BIO, DFD and OPEN have quite similar emissions today, but very different emissions in the future.

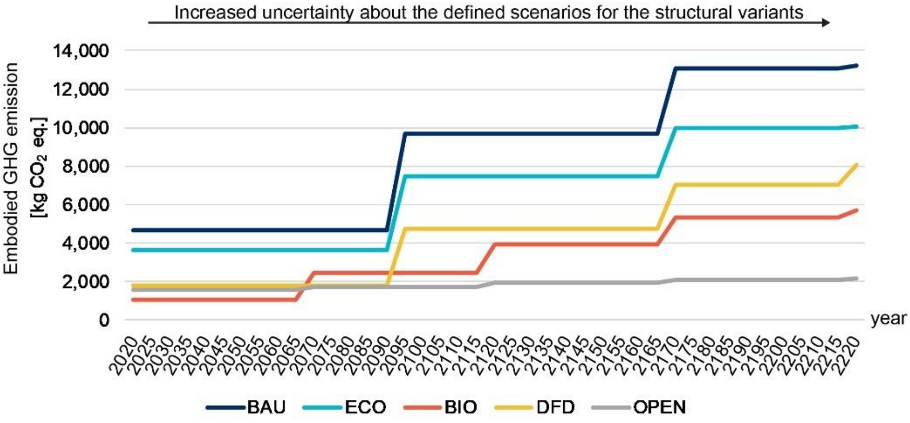


Figure 9. The structural variants' accumulated global warming potential over 200 years. Adapted from Publication 4 (Eberhardt et al., 2020d)

The long RSP captures the advantage of the long lifespan of the OPEN structure, although it fails to take into account that the uncertainty of the scenario for the variants increases over such a long time perspective. The OPEN structures may not last for 200 years for reasons other than the technical durability (e.g. location, building type and aesthetics) (Østergaard et al., 2018) and the 200 RSP is therefore questionable. Use of biomaterials and DfD could focus on shorter-lived emissions-intensive building components to reduce current emissions and make the benefits of reuse/recycling available sooner, thereby reducing the uncertainty associated with the long time-perspective. The findings of the LCA and MFA are summarised into nine design guidelines for designing circular building components that designers and decision-makers are recommended to consider.

How to design circular building components:

1) Determining, realising and guaranteeing 'ideal' circular designs requires co-design with all stakeholders in the supply chain.
2) In any project, consider not only the present production, but also the temporal aspects (i.e. future cycles).
3) Consider building components as a composite of sub-components, parts and materials with different and multiple use cycles and life cycles.
4) Consider the circular design principles and parameters in interrelation with each other i.e. material choices, expected lifespan, life cycle(s) and re-loops for each part of the building component. Single principles or parameters do not necessarily result in a more circular building component.
5) Combine circular design options to facilitate multiple VRPs as opposed to focusing on a single VRP (i.e. reuse, repair, refurbish, recycle and recover).
6) Transport should be kept to a minimum when the component is bulky or heavy (i.e. local reuse is preferable).
7) Prefer complete re-design of a building component to optimising the current linear (business-as-usual) variant, as the gain is limited.

For components with a long functional lifespan (e.g. the structure):

8) The best environmentally performing design for the structure applies the following principles:

- Uses durable materials with a very long lifespan while keeping the design as lean as possible.
- Keeps the components and materials in place for as long as possible by facilitating adaptations and adjustments over time.
- Multiple cycles of the components and materials are facilitated to prolong the use (e.g. reuse) and close the loop (e.g. recycling) before final disposal (e.g. energy recovery).

9) If the structure does not last long, then the best environmentally performing design applies the following principles:

- A lean design or use of low-impact biomaterials that have a favourable balance between: impacts/kg, technical lifespan, amount needed compared to virgin and non-renewable materials.
- Multiple cycles of the components and materials are facilitated to prolong the use (e.g. reuse) and close the loop (e.g. recycling) before final disposal (e.g. energy recovery).

The findings of Publication 4 suggest that the current industry focus on structures (e.g. cement replacements, bio-based alternatives such as cross laminated timber and DfD) and its limited focus on only one cycle at a time, does not lead to the optimum long-term environmental performance. Instead, the design guidelines entail facilitating life-prolonging designs in combination with other strategies such as biomaterials, resource efficiency and multiple cycles after end-of-use. However, the design guidelines should be perceived in light of the limited sample size tested. A broader sample representing more of the sixteen strategies identified in Publication 1, including other building components than the structure, is needed to verify the results, as only a handful of the strategies were assessed here to determine which principles are most circular. It is important to stress that different guidelines may apply for designing other short-lived and medium-lived circular building components. For example, the design guidelines for the case of a kitchen and façade, of which this dissertation has been a collaborative part, look slightly different (van Stijn, Eberhardt, Wouterszoon Jansen, & Meijer, 2020).

4.5. ADDITIONAL FINDINGS

The practical application of the developed CE LD approach and design guidelines were evaluated by 49 experts from academia, industry and government within the field of LCA and CE in the built environment.

The experts found the approach more transparent than the CFF and applicable for assessing and incentivising multiple cycles in a CE. However, the CE LD approach upon which the design guidelines are based builds on very uncertain assumptions on multiple future cycles and long lifespans. Therefore, the experts found the approach suitable for ‘ex-ante’ assessments to identify ‘ideal’ circular solutions that do not yet exist in the design stage and policymaking, and less suitable for ‘ex-post’ assessments, for example EPDs or building certification. Distinguishing between different types of cycles and their probability has been suggested to improve the accuracy of the CE LD approach (e.g. known or unknown cycles, certain or uncertain cycles, short-term or long-term cycles, open or closed cycles, and low-value or high-value cycles etc.). For example, Yamada, Daigo, Matsuno, Adachi, & Kondo (2006) calculate the average number of times a material is used in products in society from cradle to grave. Determining future cycles requires long-term collaboration with the supply chain.

The experts suggested that different types of cycles could benefit from different approaches. For example, the CE LD approach could be used for known/certain cycles or in combination with an in-depth sensitivity analysis and/or in parallel with conventional LCA for unknown/uncertain cycles. The experts recommend using the approach as an information module on multi-cycling in parallel with conventional LCA similar to the separately calculated reuse, recycling and recovery potential in module D in the EN15978/15804 standards to motivate CE while avoiding greenwashing. Furthermore, for the purpose of reducing current emissions, the experts find the EN15978/15804 preferable as the CE LD approach allocates a share of production impacts to future cycles, and this to some extent undermines the urgency of reducing emissions within the next few decades. However, it is vital to both secure contemporary and future well-being and progress.

4.6. SUMMARY OF FINDINGS

Publication 1 systematically synthesises a taxonomy of sixteen overarching CE design and construction strategies from literature. Design for assembly/disassembly, conscious material selection/substitution and design for adaptability/flexibility as well as reduce, reuse and recycle are found to be the most popular strategies and VRPs respectively. Some of the strategies may be more suitable for some buildings, components and material types than for others, such as prefabrication for identical residential housing units. Furthermore, the strategies are related in such a way that one strategy may enhance another or more strategies. Due to lack of knowledge on environmental performance, strategies are often chosen based on ‘intuition’. Independent developments in both research and industry suggest that a stronger link is needed between the two to catalyse the transition to a circular built environment.

Publication 2 compares the embodied GHG emissions of four Danish concrete buildings (a school, office, hospital and residential building) built in Denmark. The assessment finds that production, replacements and EoL accounts for 58%-68%, 11%-27% and 13%-21% of the buildings embodied GHG emissions respectively. A large reuse, recycling and recovery potential of 16%-34%, is available at the buildings’ EoL. Hence, emission-reduction strategies that reduce buildings’ current and future emissions prior to set climate targets are needed. Component groups of the structure (i.e. floors and ceilings, outer walls, roof and inner walls) make up a large share of a building’s embodied GHG emissions. The embodied GHG emissions from these component groups stem from production of concrete and aluminium, replacement of roof felt, expanded polystyrene insulation and mineral wool. A handful of CE strategies such as reuse of the concrete structure, recycling the roof felt and substitutions with wood and recycled aluminium can save between 14%-36% of the building’s embodied GHG emissions. The magnitude of the savings is, however, dependant on the building context.

The analysis in Publication 3 highlights trade-offs between qualities of different allocation approaches for the purpose of assessing multi-cycling systems. It further reveals how impact distribution differences between the allocation approaches favour certain CE strategies over others. For example, the current LCA practice following the European standards discourages DfD. None of the allocation approaches can be said to be objective, as they build on value choices making them suitable for specific contexts. Several of the assessed approaches are debatable for assessing multi-cycling systems. However, considering the limitations of the other approaches, the LD approach is, with further development, found to divide burdens between cycles more appropriately in terms of assessing and incentivising CE strategies in the building sector.

Publication 4 explores environmental and material-flow benefits of different CE strategies and derives environmental design guidelines by applying the CE LD approach developed in Publication 3 to circular variants and 19 scenarios of a structure compared to a corresponding conventional structure. The performance of the variants is much dependant on the set scenarios and time frame of the assessment. As a long time perspective is associated with high uncertainty, CE design and construction strategies such as DfD could be applied to reduce uncertainty, for example to achieve immediate impact reductions. Furthermore, single-indictor and multi-indicator assessments show different results, leading to different design decisions. Publication 4 finds that life-prolonging designs do not result in universal gain in all cases, as the benefit can also come from other factors such as material optimisations. Hence, material optimisations and CE strategies should always go hand in hand. It is found that the optimal long-term environmental performance for the structure comes from combining life-prolonging design solutions with other strategies such as biomaterials, resource-efficiency and multiple cycles after end-of-use.

CHAPTER 5. DISCUSSION

In the discussion, the findings are put into perspective by elaborating on three closely related key topics that are relevant for the development of LCA concepts that support the implementation of CE in the building sector. At the end of this chapter, a summary synthesises the topics.

5.1. TEMPORAL PERSPECTIVE OF CE IN THE BUILDING SECTOR

Publication 4 shows that designing for a long lifespan yields the best environmental performance. However, the 100-year technical lifespan of contemporary buildings in the Danish LCA method used in Publication 1 is very long compared to the 50 years used in other countries (Rønholt et al., 2019). CE introduces an even more extensive timeframe, as it considers that components and materials may have multiple different use cycles and life cycles beyond the building. For example, 240 years for the column in Publication 3 and 200 years for the structures in Publication 4. The uncertainty of future scenarios significantly increases over such a long time perspective. Temporal and spatial variations in the surrounding society as well as industrial and environmental systems may affect the environmental performance of buildings and applied CE building design and construction strategies.

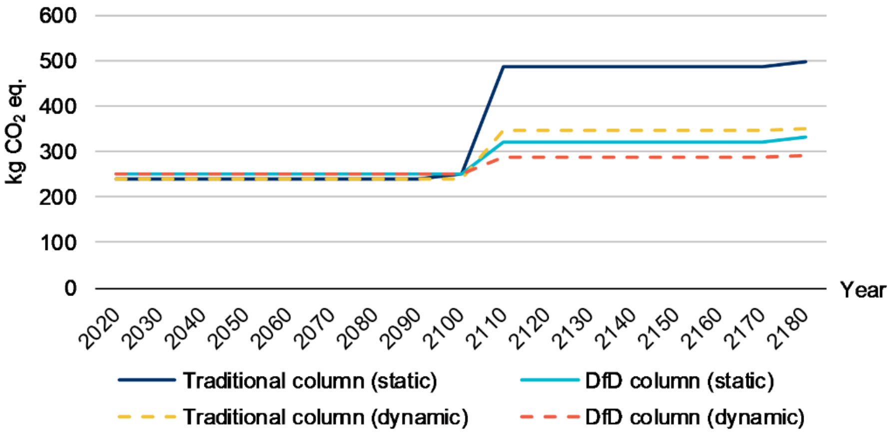


Figure 10. Embodied GHG emissions comparison of a traditional and DfD column applying static and dynamic LCA. Adapted from (Eberhardt, Birgisdottir, & Birkved, 2019).

The work in the current dissertation builds on 'static' LCA approaches using datasets that represent contemporary technologies and energy grid mixes. Figure 10 shows how the DfD concrete column in Publication 3 performs compared to a traditional column that is down-cycled after 80 years when using 'static' versus 'dynamic' LCA over just two use cycles (160 years). The static LCA provides the DfD column with a significant benefit over the traditional column. However, when considering that over time production, transportation and recycling technologies become more efficient, running on a greener energy grid-mix, the benefit of the DfD column becomes less pronounced.

The modelled embodied GHG emissions performance of the buildings' and CE design and construction strategies will change if the net-zero-emissions target is fully/partially reached by 2050. This is because modelled emissions after 2050 might not happen or they might be compensated for, for example through CO_2 storage. In this respect, modelling full and multiple use cycles and life cycles using present day datasets is flawed. Even though the handful of suggested CE design and construction strategies would significantly reduce the embodied GHG emissions over the buildings' life cycles (e.g. 36% for the office building), it is clear from the buildings' emissions profiles that the initial emissions from production are far from net zero. Thus, from the perspective of a 2050 net-zero-emissions building, short-term CE design and construction strategies (e.g. use of bio- and secondary materials) are important for reducing the building's initial GHG emissions over the next 30 years (Röck et al., 2020). From a post-2050 perspective, long-term CE design and construction strategies (e.g. DfD and adaptability) become relevant for other reasons than future embodied GHG emissions reductions such as resource scarcity and depletion. An expected doubling of the global building stock in 2050 (International Energy Agency, 2019) also means doubling the consumption of construction materials. The supply horizon for zinc and chromium, used in roofing, facades, installations etc., is predicted to be reached within the next 20 years (Remondis, 2020). The demand for gypsum is increasing, but due to reduced coal incineration, the production of industrial gypsum has been reduced (Danish Technological Institute, 2019). The demand for sand used in concrete is growing faster than natural sources can sustain (GAB report, 2018). These perspectives are important to integrate into LCA, design and decision making as well as strategic and public policy planning of contemporary buildings.

5.2. IN PRACTICE TARGETS FOR A CE

Benchmarks are needed to drive CE progress in the building sector. Although the high environmental impact savings and significantly increased material efficiency found in this PhD may support the general perception of the benefits of CE design and construction strategies, the strategies are still just compared relative to the business-as-usual building practice. Such comparisons constitute the general bottom-up benchmarking approach in building certification systems such as LEED, DGNB and BREEAM. They aim to reduce impacts (of building A) compared to the reference (building B). However, comparing with business-as-usual may not lead to sufficient optimisation, as this approach does not answer how the CE strategies perform relative to specific targets such as nearing climate goals. For this purpose, besides bottom-up reference benchmarks, there are also top-down benchmarks which often build on political targets. For example, the Paris Agreement targets a maximum of 1.5 degrees Celsius temperature rise above pre-industrial levels in response to climate change (IPCC, 2018). This target builds on a common 'carbon budget' mindset. The budget can be allocated using different sharing principles. Recent studies have defined such a budget for buildings based on the planetary boundaries framework (Rockström et al., 2009) that recognizes the Earth as a finite system and defines an environmentally safe operating space (Andersen, Ohms, et al., 2020; Brejnrod, Kalbar, Petersen, & Birkved, 2017; Habert et al., 2020; Ohms et al., 2019). These studies show how contemporary single-family houses exceed the budget considerably for several of the planetary boundaries (e.g. approximately a factor 10 overshoot of the allocated budget for climate change). It is therefore important that the CE strategies are not just applied to get 'lower' but rather 'low enough' environmental impacts.

Reference benchmarks are also associated with risk of rebound effects that can counteract the intention of reduced environmental impacts (Sorrell, 2009; Zink & Geyer, 2017). For example, bottom-up reference benchmarks have governed reduced impacts through reduced energy consumption for heating in Danish residential buildings by 45% since 1975 (Ingeniøren, 2018). However, the total energy consumption in Danish residential and office buildings has remained the same due to increases in the building stock (ibid). Similarly, CE strategies can lead to rebound effects if they fail to compete with primary production or if they lower prices and therefore increase or shift consumption (Zink & Geyer, 2017). Hence, the current reference-benchmark approach can guide the industry to choose environmentally viable CE solutions as a step towards minimising buildings' environmental impacts. However, reference benchmarks should be combined with 'budget-based' benchmarks to monitor progress towards reaching future mitigation goals. Some countries, for example Finland, are currently developing carbon budgets for buildings (Westerholm, 2020).

It is clear that CE design and construction strategies cannot suffice on their own in the pursuit of reaching the net-zero-emission target. An effective combination of all immediate emissions-reducing CE building design and construction strategies is needed as an integrated part of a larger cross-sectoral effort to reduce human-induced emissions in order to reach net-zero-emissions. This will most likely be a mix of transitioning to renewable energy and reducing overall production and consumption (Alfredsson et al., 2018; Lovins, Urge-Vorsatz, Mundaca, Kammen, & Glassman, 2019).

Circularity can be measured on other indicators than the environmental performance. For example, the economic performance tends to be overlooked (Zink & Geyer, 2017), although others are looking into this (Nußholz & Milios, 2017; Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Selection of CE strategies can be biased by the choice of the metric (Niero & Kalbar, 2019). Hence, MCDA methods are needed to fully assess circularity in the built environment. Furthermore, resource efficiency benefits of

CE principles cannot alone be assessed in LCA using the environmental impact category ADPe, because the impact potential peaks for virgin metals that are usually very recyclable and shows less benefit from more challenging building materials such as reusing concrete elements (Eberhardt et al., 2018a). In addition, the shorter RSP used in building LCAs (50 years) does not capture the benefits of long-lasting solutions. These challenges suggest that assessments, such as MFA, and additional LCAs using longer RSP and MCDA are needed in parallel with LCA to fully support the development and implementation of CE in general.

Caution about greenwashing is urged when allocating impacts to uncertain future cycles in LCA, as in the developed CE LD approach. A balance between reducing up-front emissions to achieve approaching climate targets on the one hand, and transition to CE processes on the other, should be considered from both a political and ethical point of view.

5.3. CE SYSTEM VERSUS PRODUCT PERSPECTIVE

The CE concept recognizes that buildings’ components and materials are connected to systems and processes outside of the built environment to narrow, slow and close material loops. Therefore, CE is relevant at multiple levels that are connected: global, national, local, value chains, building, product, material etc. CE is typically applied to the level relevant for the individual stakeholders, most often the product level, rather than the full system level (Reike et al., 2018). Similarly, the European LCA standards used in the construction sector focus on the product perspective relevant for building owners and product manufacturers. The European standards apply attributional LCA, in which a product is ‘separated’ from the rest of the economic system. Although work in this PhD considers an extended system for circular building components and materials, it relies on attributional LCA where the environmental impact potentials that can be attributed to the building components and materials are quantified (Hauschild et al., 2018). Therefore, the recommendations of the dissertation are only valid at building component and material level and cannot be directly projected to societal level. The recommendations are also site-specific (i.e. a Danish context) and cannot be directly translated to other countries. On a societal level, an enlarged system perspective that considers the interdependencies between different product systems is important to support decisions that move entire societies towards CE. An example of a necessary, enlarged system-scale assessment is the banning of single-use plastic cutlery, plates, cotton buds, straws etc. by 2021 in the EU as part of the EU’s transition towards a CE (European Commission, 2019a). This will increase the demand for reusable, recyclable and bio-based substitutes, which may lead to unintended consequences in marginal production. For example, if the demand for bio-based materials surpasses the regeneration rate of the forest stock, or if the demand for reusable recyclable substitutes increases environmental impacts from production and recycling of reusable and recyclable substitutes such as metals and glass. Hence, different CE initiatives need supplementary environmental performance assessments at a larger system level to monitor that the larger system is progressing towards the set climate targets. Within LCA, system-level assessments can be performed using consequential LCA. Consequential LCA involves modelling a broader system that the decision to be made, based on the LCA results, affects (Ekvall & Weidema, 2004). Consequential LCA has, however, not yet been adopted by the building sector in practice.

Unintended consequences may also arise from a one-eyed focus on GWP. GWP is commonly used in environmental impact assessments in the building sector (Hossain & Ng, 2018; Pomponi & Moncaster, 2016; Röck et al., 2020) as well as in recent CE studies (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012; Nasir et al., 2017). GWP is a relatively good indicator for some other impact categories in more comprehensive impact assessment methods (e.g. ReCiPe) in a building context, given a high coverage in the LCI (Heinonen, Säynäjoki, Junnonen, Pöyry, & Junnila, 2016; Marsh, 2016). However, GWP is not universally correlated to all impact categories (e.g. toxicological impacts) (Laurent, Olsen, & Hauschild, 2010). Hence, environmental gains in one impact category can come with trade-offs in other categories, as also demonstrated for some of the CE design and construction strategies in Publication 4. Therefore, other environmental areas of protection need to be considered in the implementation of CE strategies.

The EN 15978/15804 cut-off allocation approach can be characterized as risk-aversive, by focusing on reducing current emissions following a polluter-pays principle. However, Publication 3 demonstrates how this allocation practice does not fully capture the advantages of multi-cycling/cascading systems and favours recycling over reuse from a product perspective. However, a system perspective is needed, as several CE strategies in effective combinations are needed from both a pre-2050 and post-2050 net-zero-emissions-target perspective.

5.4. SUMMARY OF DISCUSSION

The discussion present three closely related core topics pertaining to implementation of CE in the building sector supported by LCA.

First, the temporal perspective is of utmost importance for developing LCA tools that support the implementation of CE design and construction strategies. Considering potentially significant temporal factors in the surrounding society as well as industrial and environmental systems that may affect the CE strategies' performance can provide a better decision basis on which strategies to choose based on the LCA results. Furthermore, decisions on CE design and construction strategies should focus on a timescale consistent with the response to climate change, resource scarcity and depletion as well as other global challenges. For example, a pre-2050 net-zero-emissions-target perspective implies a prevalent focus on reducing immediate emissions related to buildings' production and post-2050 perspective implies a prevalent focus on future resource scarcity and depletion and other important environmental areas of protection.

Second, in relation to this, LCA benchmarks are essential to catalyse CE progress in the building sector. The current industry focus on reference benchmarks should be supplemented with ‘budget-based’ benchmarks to limit the emissions ‘allowed’ within the shrinking budget of emissions towards the net-zero-emissions target in 2050. It is clear that an effective combination of all immediate emissions-reducing CE building design and construction strategies as part of a larger cross-sectoral effort is needed to reach the net-zero-emissions target by 2050. However, CE is also concerned with other aspects than environmental impacts. Assessment methods such as MCDA, MFA and additional LCAs using longer RSP are needed, in parallel with the current LCA practice to consider other circularity indicators such as economic performance and resource efficiency, in order to fully assess circularity and to avoid biased decisions based on the choice of measurement. Allocating impacts to future cycles in LCA can stimulate CE, but can also lead to greenwashing. Hence, a balance between reducing up-front emissions and transitioning to CE processes should be both politically and ethically considered.

The third topic concerns the larger societal setting of which the building sector is a part of. While CE building design and construction strategies can optimise the performance of individual buildings and components, it is equally important to ensure that the overall societal system is also progressing towards climate targets. This requires a larger system perspective beyond the current product focus of the European LCA standards for buildings. Furthermore, an enlarged system perspective is also needed to fully capture the advantages of multi-cycling/cascading systems within LCA.

This PhD illustrates that there is a whole range of influencing parameters that may affect the environmental performance of CE design and construction strategies. These parameters may need to be implemented into the current LCA practice for building design to provide a level of confidence when basing the adoption of CE building design and construction strategies on LCA results.

CHAPTER 6. CONCLUSIONS

This dissertation has provided the Danish building sector with: 1) a taxonomy of prevalent CE building design and construction strategies, 2) an overview of embodied GHG emissions profiles of four prevalent Danish building types and identified CE opportunities to reduce the buildings' embodied GHG emissions, 3) developed an LCA allocation approach that supports the implementation of CE in the building sector, 4) an overview of the environmental performance of selected CE building design and construction strategies, and 5) environmental design guidelines for designing circular building components. The main research question and the four sub questions are recapped below, and the main research question synthesises the findings from the four sub questions:

Main research question: *How can LCA support the implementation of CE principles in the building sector to reduce buildings' environmental impacts?*

This dissertation discloses how the building industry's current LCA and building practice is limited in its scope for assessing and supporting the implementation of CE to facilitate reaching the net-zero-emissions target by 2050. The current LCA practice in the building sector can help identify opportunities for implementing CE initiatives and gradually reduce the embodied GHG emissions in current building practices. An assessment of four Danish concrete buildings found that notable embodied GHG emissions savings can be achieved (14%-36%) by applying a handful of combined CE strategies such as reusing the concrete structure, recycling roof felt, using wood and secondary aluminium. However, these savings are far from the emission reductions needed to reach net-zero-emissions by 2050. Hence, societal targets necessitate a change in the CE design and LCA practice in the building sector. There is a need to effectively combine several low-carbon CE design and construction strategies. Furthermore, the building sector's LCA practice, focusing on single life cycles, discourages the multi-cycling/cascading aspect of CE. Thus, some CE strategies are given a supreme advantage over other important strategies. By further developing an existing environmental-impact-sharing principle, that extends the scope of the current LCA practice, the dissertation demonstrates how LCA can support assessment of, and incentivise designing for, multiple cycles in a circular system in the building sector. However, further development of CE assessment methods and CE design practice in the building sector must integrate a timescale consistent with the response to climate change, resource scarcity and depletion as well as other global challenges to reach societal targets. Pre-2050 indicates primary focus on reducing immediate emissions related to buildings' production, while post-2050 could indicate a shift in focus to future resource scarcity and depletion and other important environmental areas of protection. It is important to acknowledge the need for CE, as resource scarcity will not be solved in 2050 alone on the basis of carbon capture and low-carbon strategies. Furthermore, LCA cannot alone assess all aspects of CE, and it is therefore recommended that multiple assessment approaches are applied in parallel with LCA (e.g. MCDA, MFA, LCA with long RSP) to fully support the development and implementation of CE. While the findings of the dissertation are a step on the way towards a building sector in line with planetary boundaries, such as GHG emissions, extensive efforts that go beyond the building sector are needed to identify and implement several CE strategies in effective combination with one another to progress society towards net-zero-emissions and accommodate resource scarcity.

Sub-question 1: *Which design and construction strategies are being related to CE?*

A systematic review mapped sixteen state-of-the-art design and construction strategies related to CE. The review revealed focus on assembly/disassembly, material selection/substitution and adaptability/flexibility with focus on the VRPs reduce, reuse and recycle. The reviewed literature suggests that some strategies seem more beneficial for some buildings and components than for others. For example, prefabrication and modularity for identical housing units. The strategies seem to be interconnected in the sense that one strategy may aid other strategies. Lack of knowledge on the strategies' environmental performance leads to intuitive strategy choices. Separate developments in academia and industry were also revealed, suggesting a need for closer collaboration between theory and practice to progress CE in the building sector.

Sub-question 2: *Which life cycle stages, building components and materials induce the largest environmental impact potentials within prevailing Danish building types?*

To answer this, the embodied GHG emissions profiles of four Danish concrete buildings, representing different prevailing building types, were compared. The comparison shows that CE design and construction strategies should focus on reducing the high share of immediate embodied GHG emissions (58%-68%) stemming from the buildings' production, corresponding to the urgency of nearing targets and suggested tipping points. However, focus should also be on reducing the share of embodied GHG emissions (11%-27%) emanating from future emissions from replacements taking place before the climate goals. Notable saving potentials pertain to subsequent use of the materials at the buildings' EoL, but this is associated with high uncertainty as savings are gained sometime in the future. The embodied GHG emissions are concentrated around central component groups of the structure (i.e. floors, ceilings, outer walls, roof and inner walls) stemming from a handful of materials (i.e. production of concrete and aluminium, incineration of roof felt and expanded polystyrene and production of mineral wool).

Sub-question 3: *How do different allocation approaches affect the LCA outcome and the incentive for CE when using them to assess different CE building design and construction strategies?*

Through a comparison of four LCA allocation approaches applied to four cases of circular building components, this dissertation unveils trade-offs between different qualities of the different approaches. These trade-offs arise from the approaches' different value choices that make them suitable for specific contexts. In line with the value choices, each allocation approach encourages or discourages certain CE strategies. The dissertation reveals how the current LCA practice in the building sector discourages DfD and is questionable in assessing and incentivising multi-cycling systems due to its limited focus on single cycles. The dissertation finds that dividing impacts of shared components and materials over the number of cycles in a system that share them can provide shared responsibility and benefits for all cycles, thereby stimulating designing for narrowing, slowing and closing current and future loops in line with the CE concept.

Sub-question 4: *Which design and construction strategies result in the largest environmental impact savings?*

To answer this, the average LCA and MFA benefits of different CE design and construction strategies were assessed for the case of a building structure for a 200-year RSP. The strategies' performance proved to be both temporal and context-dependant. For example, a long RSP captures the advantage of life-prolonging strategies, but different life-prolonging strategies do not provide universal gains in all cases, as other design factors such as material choice also affect the performance of the strategy. A combination of multiple CE circular design and construction strategies provides the best long-term environmental performance. For example, combining biomaterials with multiple VRPs and long use or combining resource-efficiency, long use via adaptability, partial use of biomaterials and multiple cycles after end of use. Thus, applying CE principles to optimise the environmental performance of buildings is a matter of combining the right design principles and parameters (i.e. CE design and construction strategies, VRPs, lifespans, material types etc.). The research also shows how single-indiator and multi-indicator assessment can lead to different environmental performances, ultimately leading to different design decisions. The listed design guidelines in Section 4.4 are recommended to serve as points of attention when designing circular building components. These design guidelines should, however, be perceived in light of the limited number of CE building design and construction strategies tested on the single case of a building structure.

6.1. FUTURE RESEARCH

Future research within the field of environmental-impact-reducing CE design and construction strategies and environmental design guidelines for implementation in practice should increase the selection of assessed strategies on more building component groups. Furthermore, research should systematically explore which strategy combinations contribute to effective CE in the built environment based on a timescale corresponding to the response to climate change, resource scarcity and other global challenges. In that regard, research should increase focus on the resource scarcity benefits of CE.

Future research within the field of mapping the embodied GHG emissions profile of buildings should broaden the sample size to include more cases from different data sources, including additional types of buildings, for example steel and wood structures, to ensure that common conclusions are valid in a broader perspective.

Future research within the field of CE benchmarks for buildings should, in combination with bottom-up reference benchmarks, develop top-down ‘budget based’ benchmarks to ensure that CE efforts contribute to staying within a confined environmental budget to reach future mitigation goals.

Future research within the field of LCA methodological developments for assessing CE in practice should include testing on a larger sample of circular building components, VRPs and environmental impact categories. Furthermore, research should elaborate on how best to implement CE into LCA practice and how best to reduce uncertainty associated with buildings’ long lifespan and multiple future cycles.

Future research within the larger societal focus on CE should consider how CE will change market structures and potentially generate feedback effects. Furthermore, research should elaborate on how to best project the findings of this dissertation on a larger country scale (e.g. Denmark). Research should evaluate aspects concerning the societal level of CE using MCDA and consequential LCA.

LITERATURE LIST

Aagaard, N.-J., Brandt, E., Aggerholm, S., & Haugbølle, K. (2013). *Levetider af bygningsdele ved vurdering af bæredygtighed og totaløkonomi*.

Adams, K. T., Osmani, M., Thorpe, T., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Proceedings of the Institution of Civil Engineers - Waste and Resource Management*, *170*(1), 15–24. https://doi.org/10.1680/jwarm.16.00011

Alfredsson, E., Bengtsson, M., Brown, H. S., Isenhour, C., Lorek, S., Stevis, D., & Vergragt, P. (2018). Why achieving the Paris Agreement requires reduced overall consumption and production. *Sustainability: Science, Practice, and Policy*, *14*(1), 1–5. https://doi.org/10.1080/15487733.2018.1458815

Allacker, K., Mathieux, F., Manfredi, S., Pelletier, N., De Camillis, C., Ardente, F., & Pant, R. (2014). Allocation solutions for secondary material production and end of life recovery: Proposals for product policy initiatives. *Resources, Conservation and Recycling*, *88*, 1–12. https://doi.org/10.1016/j.resconrec.2014.03.016

Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, *22*(9), 1441–1458. https://doi.org/10.1007/s11367-016-1244-0

Anand, C. K., & Amor, B. (2017). Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renewable and Sustainable Energy Reviews*, *67*, 408–416. https://doi.org/10.1016/j.rser.2016.09.058

Andersen, C. E., Kanafani, K., Zimmermann, R. K., Rasmussen, F. N., & Birgisdóttir, H. (2020). Comparison of GHG emissions from circular and conventional building components. *Buildings and Cities*, *1*(1), 379. https://doi.org/10.5334/bc.55

Andersen, C. E., Ohms, P., Rasmussen, F. N., Birgisdóttir, H., Birkved, M., Hauschild, M., & Ryberg, M. (2020). Assessment of absolute environmental sustainability in the built environment. *Building and Environment*, *171*(October 2019). https://doi.org/10.1016/j.buildenv.2019.106633

Anderson, J., Ronning, A., & Moncaster, A. (2019). The Reporting of End of Life and Module D Data and Scenarios in EPD for Building level Life Cycle Assessment. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012051

Assefa, G., & Ambler, C. (2017). To demolish or not to demolish : Life cycle consideration of repurposing buildings. *Sustainable Cities and Society*, *28*, 146–153. https://doi.org/10.1016/j.scs.2016.09.011

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated resuable building modules. *Energy and Buildings*, *47*, 159–168.

Birgisdottir, H., Moncaster, A., Wiberg, A. H., Chae, C., Yokoyama, K., Balouktsi, M., … Malmqvist, T. (2017). IEA EBC annex 57 ‘evaluation of embodied energy and CO2eq for building construction.’ *Energy and Buildings*, *154*, 72–80. https://doi.org/10.1016/j.enbuild.2017.08.030

Birgisdottir, H., Houlihan-Wiberg, A., Malmqvist, T., Moncaster, A., & Nygaard Rasmussen, F. (2016). *IEA EBC Annex 57 - Strategies for Reducing Embodied Energy and Embodied GHG Emissions: Guidelines for Designers and Consultants - Part 2*.

Birgisdottir, H., Houlihan-Wiberg, A., Malmqvist, T., Moncaster, A., & Rasmussen, F. N. (2016). *IEA EBC ANNEX 57 - Subtask 4: Case studies and recommendations for the reduction of embodied energy and embodied greenhouse gas emissions from buildings*.

Birgisdottir, H., Kanafani, K., Zimmermann, R. K., Andersen, C. M. E., Hatic, D., Elmbæk, M., … Sack-Nielsen, T. (2019). *Dialogværktøj: Cirkulær værdiskabelse i den eksisterende bygningsmasse (Dialog tool: circular value creation in the existing building mass)*. Copenhagen.

Birgisdottir, H., & Nygaard Rasmussen, F. (2019). Development of LCAbyg : A National Life Cycle Assessment Tool for Buildings in Denmark. *IOP Conference Series: Earth and Environmental Science*, (209). https://doi.org/10.1088/1755-1315/290/1/012039

Birgisdottir, H., & Rasmussen, F. N. (2019). Development of LCAbyg: A National Life Cycle Assessment Tool for Buildings in Denmark. *IOP Conference Series: Earth and Environmental Science*, *290*(1). https://doi.org/10.1088/1755-1315/290/1/012039

Blomsma, F., & Brennan, G. (2017). The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. *Journal of Industrial Ecology*, *21*(3), 603–614. https://doi.org/10.1111/jiec.12603

Blomsma, F., Kjaer, L., Pigosso, D., McAloone, T., & Lloyd, S. (2018). Exploring Circular Strategy Combinations - Towards Understanding the Role of PSS. *Procedia CIRP*, *69*(May), 752–757. https://doi.org/10.1016/j.procir.2017.11.129

Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Boulding, K. (1996). The economics of the coming spaceship earth. In H. Jarret (Ed.), *Environmental quality in a growing economy - essay from the sixth RFF forum* (pp. 3–14). Baltimore, MD: The Johns Hopkins University Press.

Brand, S. (1994). *How Buildings Learn: What Happens After They’re Built*. Viking Press.

Braungart, M., & McDonough, W. (2002). *Cradle to cradle: Remaking the way we make things* (1st ed.). New York: North Point.

Brejnrod, K. N., Kalbar, P., Petersen, S., & Birkved, M. (2017). The absolute environmental performance of buildings. *Building and Environment*, *119*, 87–98. https://doi.org/10.1016/j.buildenv.2017.04.003

Brezet, J. C., & van Hemel, C. G. (1997). *Ecodesign: A promising approach to sustainable production and consumption*. Paris: United Nations Environ- ment Program.

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

Cederstrand, P., Riise, E., & Uihlein, A. (2014). *Evaluation of recycling and allocation methods for paper*.

Cheshire, D. (2016). *Building revolutions applying the circular economy to the built environement*. Newcastle upon Tyne: RIBA Publishing.

CLEAN. (2014). *Kortlægning af genbrugsmarkeder for byggematerialer [Mapping of recycling markets for building materials]*.

Climate Council. (2020). *Kendte veje og nye spor til 70 procents reduktion (Known roads and new tracks to a 70 percent reduction)*. Retrieved from https://www.klimaraadet.dk/da/rapporter/kendte-veje-og-nye-spor-til-70-procents-reduktion

Crowther, P. (2005). Design for disassembly - themes and principles. In *RAIA/BDP Environment Design Guide*. https://doi.org/10.1115/1.2991134

Dahlsrud, A. (2008). How corporate social responsibility is defined: An analysis of 37 definitions. *Corporate Social Responsibility and Environmental Management*, *15*(1), 1–13. https://doi.org/10.1002/csr.132

Danish EPA. (2017). *Affaldsforebyggelse i byggeriet (Waste prevention in construction)*. https://doi.org/10.1007/s10493-007-9071-4

Danish Technological Institute. (2019). *Materialer i den cirkulære økonomi: Gips*.

Danish Transport and Construction Agency. (2020). *Vejledning om den frivillige bæredygtigheds klasse*.

Danske ARK & FRI. (2017). *Rådgivning om bæredygtighed i byggeriet 2017*. 18. Retrieved from https://www.danskeark.dk/sites/default/files/2017-12/Tillaeg_ydelsesbeskrivelser_baeredygtighed_0.pdf

Dautremont, C., Jancart, S., Dagnelie, C., & Stals, A. (2019). Parametric design and BIM, systemic tools for circular architecture. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012071

de Almeida Biolchini, J. C., Mian, P. G., Natali, A. C. C., Conte, T. U., & Travassos, G. H. (2007). Scientific research ontology to support systematic review in software engineering. *Advanced Engineering Informatics*, *21*(2), 133–151. https://doi.org/10.1016/j.aei.2006.11.006

De Wolf, C., Hoxha, E., & Fivet, C. (2020). Comparison of environmental assessment methods when reusing building components: A case study. *Sustainable Cities and Society*, *61*(June), 102322. https://doi.org/10.1016/j.scs.2020.102322

Delem, L., & Wastiels, L. (2019). The practical use of module D in a building case study: Assumptions, limitations and methodological issues. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012048

Densley Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Production*, *148*, 642–652. https://doi.org/10.1016/j.jclepro.2017.02.006

Densley Tingley, D., & Davison, B. (2012). Developing an LCA methodology to account for the environmental benefits of design for deconstruction. *Building and Environment*, *57*, 387–395. https://doi.org/10.1016/j.buildenv.2012.06.005

Di Maria, A., Eyckmans, J., & Van Acker, K. (2018). Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Management*, *75*, 3–21. https://doi.org/10.1016/j.wasman.2018.01.028

Eberhardt, L. C. M., Birgisdottir, H., & Birkved, M. (2019). Dynamic Benchmarking of Building Strategies for a Circular Economy. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012027

Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. (2018a). Life cycle assessment of a Danish office building designed for disassembly. *Building Research & Information*, *47*(6), 666–680. https://doi.org/10.1080/09613218.2018.1517458

Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. (2018b). The Potential of Circular Economy in Sustainable Buildings. In I. Press (Ed.), *World multidiciplinary civil engineering architectural urban planning symposium* (pp. 1–10). Retrieved from https://findit.dtu.dk/en/catalog/2435427024

Eberhardt, L. C. M., Birkved, M., & Birgisdottir, H. (2020a). Building design and construction strategies for a circular economy. *Architectural Engineering and Design Management*, *0*(0), 1–21. https://doi.org/10.1080/17452007.2020.1781588

Eberhardt, L. C. M., Rønholt, J., Birgisdottir, H., & Birkved, M. (2020b). Circular Economy potential within the building stock - mapping the embodied greenhouse gas emissions of four Danish examples. *Building Engineering*.

Eberhardt, L. C. M., van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020c). Development of a life cycle assessment allocation approach for circular economy in the built environment. *Submitted to International Journal of Building & Environment*.

Eberhardt, L. C. M., van Stijn, A., Stranddorf, L., Birkved, M., & Birgisdóttir, H. (2020d). Environmental design guidelines for circular building components: the case of the circular building structure. *Submitted to Environmental Management*.

Edmondson, A. C., & Mcmanus, S. E. (2007). Methodological fit in management field research. *Academy of Management Review*, *32*(4), 1246–1264. https://doi.org/10.5465/amr.2007.26586086

EEA. (2019). *The European environment - state and outlook 2020: Knowledge for transition to a sustainable Europe*. https://doi.org/10.15196/TS600305

Ekvall, T., & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *International Journal of Life Cycle Assessment*, *9*(3), 161–171. https://doi.org/10.1007/BF02994190

Ellen MacArthur Foundation. (2012). *Towards the Circular Economy - Economic and business rationale for an accelerated transition* (Vol. 1). https://doi.org/10.1162/108819806775545321

Ellen MacArthur Foundation. (2015a). Growth within: a circular economy vision for a competitive europe. *Ellen MacArthur Foundation*, 100. https://doi.org/Article

Ellen MacArthur Foundation. (2015b). *Potential For Denmark As A Circular Economy - A case study from: Delivering the Circular Economy - A Toolkit for Policy Makers*.

Ellen MacArthur Foundation. (2016). *Circularity in the Built Environment: Case Studies*. Retrieved from https://www.ellenmacarthurfoundation.org/assets/downloads/Built-Env-Co.Project.pdf

Ellen MacArthur Foundation, & Granta design. (2015). *Circularity indicators: An approach to measuring circularity*. Cowes: Ellen MacArthur Foundation.

EN 15804. (2013). *Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012*.

EN 15978. (2011). *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method*.

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

European Commission. (2008). Directive 2008/98/EC on waste (Waste Framework Directive). Retrieved November 11, 2018, from http://ec.europa.eu/environment/waste/framework/

European Commission. (2017). *Circular Economy Research and Innovation - Connecting economic & environmental gains*. https://doi.org/10.2777/416618

European Commission. (2019a). Circular Economy: Commission welcomes Council final adoption of new rules on single-use plastic litter. Retrieved November 11, 2020, from https://ec.europa.eu/commission/presscorner/detail/en/IP_19_2631

European Commission. (2019b). *Going climate neutral by 2050 a strategic longterm vision for a prosperous, modern, competetive and climate-neutral EU economy*. Luxemborg.

European Commission. (2020a). *A new Circular Economy Action Plan for a cleaner and more competetive Europe*. https://doi.org/10.1017/CBO9781107415324.004

European Commission. (2020b). *Circular Economy principles for Buildings Design*.

European Parliament and the Council of the European Union. (2018). Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. In *Official Journal of the European Union*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1530557218036&uri=CELEX:32018L0851

Flyvbjerg, B. (2006). Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, *12*(2), 219–245. https://doi.org/10.1177/1077800405284363

French, M. L., & Laforge, R. L. (2006). Closed-loop supply chains in process industries: An empirical study of producer re-use issues. *Journal of Operations Management*, *24*(3), 271–286. https://doi.org/10.1016/j.jom.2004.07.012

Frischknecht, R., Birgisdottir, H., Chae, C. U., Lützkendorf, T., & Passer, A. (2019). IEA EBC Annex 72 - Assessing life cycle related environmental impacts caused by buildings - Targets and tasks. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012042

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

Frischknecht, R., Ramseier, L., Yang, W., Birgisdottir, H., Chae, C-U., Lützkendorf, T… Hoxa, E. (2020). Compariosn of the greenhouse gas emissions of a high-rise residential building assessed with differetn national LCA approaches - IA EBC Annex 72. In press: *IOP Conference Series: Earth and Environmental Science 588*, 022029.

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

Frosch, R. A., & Gallopoulos, N. E. (1989). Strategies for manufacturing. *Scientific American*, 261(3), 144–152.

GAB report. (2018). Sand Scarcity in the Construction Industry. Retrieved November 9, 2020, from https://www.gabreport.com/sand-scarcity-in-the-construction-industry

Gallego-Schmid, A., Chen, H. M., Sharmina, M., & Mendoza, J. M. F. (2020). Links between circular economy and climate change mitigation in the built environment. *Journal of Cleaner Production*, *260*, 121115. https://doi.org/10.1016/j.jclepro.2020.121115

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geldermans, R. J. (2016). Design for Change and Circularity - Accommodating Circular Material & Product Flows in Construction. *Energy Procedia*, *96*(October), 301–311. https://doi.org/10.1016/j.egypro.2016.09.153

Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. C. L. (2016). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, *66*, 344–357. https://doi.org/10.1016/j.omega.2015.05.015

Ghisellini, P., Cialani, C., & Ulgiati, S. (2015). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, pp. 1–22. https://doi.org/10.1016/j.jclepro.2015.09.007

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*(November), 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *Journal of Cleaner Production*, *178*, 618–643. https://doi.org/10.1016/j.jclepro.2017.11.207

Giesekam, J., Barrett, J. R., & Taylor, P. (2016). Construction sector views on low carbon building materials. *Building Research and Information*, *44*(4), 423–444. https://doi.org/10.1080/09613218.2016.1086872

Giesekam, J., & Pomponi, F. (2017). Briefing: Embodied carbon dioxide assessment in buildings: guidance and gaps. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*. https://doi.org/10.1680/jensu.17.00032

Green Building Council Denmark. (2020). DGNB DK. Retrieved February 28, 2020, from https://www.dk-gbc.dk/english/

Gustavsson, L., Pingoud, K., & Sathre, R. (2006). Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings. *Mitigation and Adaptation Strategies for Global Change*, *11*(3), 667–691. https://doi.org/10.1007/s11027-006-7207-1

Habert, G., Röck, M., Steininger, K., Lupísek, A., Birgisdottir, H., Desing, H., … Lützkendorf, T. (2020). Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. *Buildings and Cities*, *1*(1), 429–452. https://doi.org/10.5334/bc.47

Habraken, N. J. (1972). *Supports: An Alternative to Mass Housing*. London: Urban International Press.

Haney, W., Russel, M., Gulek, C., & Fierros, E. (1998). Drawing on Education: Using Student Drawings to Promote Middle School Improvement. *Schools in the*

Middle, *7*(3), 38–43. Retrieved from https://eric.ed.gov/?id=EJ561666

Harsh, S. (2011). Purposeful Sampling in Qualitative Research Synthesis. *Qualitative Research Journal*, *11*(2), 63–75. Retrieved from https://search.proquest.com/docview/920894910/41BC710066204835PQ/1?accountid=13042

Hart, J., Adams, K., Giesekam, J., Tingley, D. D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: The case of the built environment. *Procedia CIRP*, *80*, 619–624. https://doi.org/10.1016/j.procir.2018.12.015

Hauschild, M., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life Cycle Assessment - Theory and practice*. https://doi.org/10.1007/978-3-319-56475-3

Heeren, N., & Hellweg, S. (2019). Tracking Construction Material over Space and Time: Prospective and Geo-referenced Modeling of Building Stocks and Construction Material Flows. *Journal of Industrial Ecology*, *23*(1), 253–267. https://doi.org/10.1111/jiec.12739

Heinonen, J., Säynäjoki, A., Junnonen, J. M., Pöyry, A., & Junnila, S. (2016). Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator? *Building and Environment*, *95*, 116–125. https://doi.org/10.1016/j.buildenv.2015.09.006

Hellweg, S., & Mila i Canals, L. (2014). Emerging approaches, challenges and opportunities in life cycle assessment. *Science*, *344*(6188), 1109–1113. https://doi.org/10.1126/science.1248361

Hollberg, A., Lützkendorf, T., & Habert, G. (2019). Using a budget approach for decision-support in the design process. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012026

Hopkinson, P., Chen, H. M., Zhou, K., Wang, Y., & Lam, D. (2019). Recovery and reuse of structural products from end-of-life buildings. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, *172*(3), 119–128. https://doi.org/10.1680/jensu.18.00007

Hossain, M. U., & Ng, S. T. (2018). Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. *Journal of Cleaner Production*, *205*, 763–780. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.09.120

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. *Renewable and Sustainable Energy Reviews*, *130*(May), 109948. https://doi.org/10.1016/j.rser.2020.109948

Ingeniøren. (2018). Minister lover flere besparelser, men afviser forskernes anbefalinger (Minister promises additional savings but reject researchers' recommendations). Retrieved November 10, 2020, from https://ing.dk/artikel/minister-lover-flere-besparelser-afviser-forskernes-anbefalinger-204859

Innovation Fund Denmark. (2020). *Cirkulært Byggeri – Omstilling af byggesektoren til cirkulær ressourceøkonomi (Circular Construction - Transition of the construction sector to a circular resource economy)*. Retrieved from https://innovationsfonden.dk/sites/default/files/2019-10/call_saerligt_erhvervsforskeropslag_cirkulaert_byggeri.pdf

International Energy Agency. (2019). *Global Status Report for Buildings and Constructi on Towards a zero-emissions, efficient and resilient buildings and constructi on sector*. Retrieved from www.iea.org

IPCC. (2018). *Global warming of 1.5° C An IPPC Special Report*. Retrieved from www.environmentalgraphiti.org

IRP. (2017). *Assessing Global Resource Use: A systems approach to resource efficiency and pollution reduction*. A report of the International Resource Panel. United Nations Environment Programme. Nairoby, Kenya.

IRP. (2019). *Global Resources Outlook 2019: Natural Resources for the Future We Want. A Report of the International Resource panel*. Nairobi, Kenya.

ISO 14040. (2008). Environmental management - Life cycle assessment - Principles and framework. In *Order A Journal On The Theory Of Ordered Sets And Its Applications*.

ISO 14044. (2006). *Environmental management - Life cycle assessment - Requirements and guidelines*.

ISO 21931-1. (2010). *Sustainability in building construction Framework for methods of assessment of the environmental performance of construction works Part 1: Buildings*.

John, V. (2012). *Derivation of reliable simplification strategies for yje comparative LCA of individual and "typical" newly built Swiss apartment buildings*. (20608).

Jones, C. I. (2009). Embodied impact assessment: The methodological challenge of recycling at the end of building lifetime. *Const. Inf.*, *11*, 140–146. Retrieved from https://www.researchgate.net/publication/284105479_Embodied_impact_assessment_The_methodological_challenge_of_recycling_at_the_end_of_building_lifetime

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

Kanafani, K., Zimmermann, R. K., Birgisdottir, H., & Rasmussen, F. N. (2019). *LCA i tidlig bygningsdesign: Introduktion til metoden og eksempler på miljøprofiler (LCA in early building design: Introduction to the method and examples of environmental profiles)*. Retrieved from http://vbn.aau.dk/da/publications/lca-i-tidlig-bygningsdesign(f7a0dbc9-4fe2-4d29-934e-b2c40d820a5e).html

Kibert, C. J. (2007). The next generation of sustainable construction. *Building Research & Information*, *35:6*, 506–601. https://doi.org/10.1080/09613210701467040

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, pp. 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Koffler, C. (2018). Are we still keeping it real? Proposing a revised paradigm for recycling credits in attributional life cycle assessment. *International Journal of Life Cycle Assessment*, 181–190.

König, H., & De Cristofaro, M. L. (2012). Benchmarks for life cycle costs and life cycle assessment of residential buildings. *Building Research and Information*, *40*(5), 558–580. https://doi.org/10.1080/09613218.2012.702017

Kyrö, R., Jylhä, T., & Peltokorpi, A. (2019). Embodying circularity through usable relocatable modular buildings. *Facilities*, *37*(1–2), 75–90. https://doi.org/10.1108/F-12-2017-0129

Laurent, A., Olsen, S. I., & Hauschild, M. Z. (2010). Carbon footprint as environmental performance indicator for the manufacturing industry. *CIRP Annals - Manufacturing Technology*, *59*(1), 37–40. https://doi.org/10.1016/j.cirp.2010.03.008

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lignatur. (2020). LIGNATUR element. Retrieved October 15, 2020, from https://www.lignatur.ch/en/product/lignatur-element

Love, P. E. D., Edwards, D. J., & Irani, Z. (2012). Moving beyond optimism bias and strategic misrepresentation: An explanation for social infrastructure project cost overruns. *IEEE Transactions on Engineering Management*, *59*(4), 560–571. https://doi.org/10.1109/TEM.2011.2163628

Lovins, A. B., Urge-Vorsatz, D., Mundaca, L., Kammen, D. M., & Glassman, J. W. (2019). Recalibrating climate prospects. *Environmental Research Letters*, *14*(12). https://doi.org/10.1088/1748-9326/ab55ab

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., & Nygaard, F. (2018). Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. *Energy and Buildings*, *166*, 35–47. https://doi.org/10.1016/j.enbuild.2018.01.033

Marsh, R. (2016). LCA profiles for building components: Strategies for the early design process. *Building Research and Information*, *44*(4), 358–375. https://doi.org/10.1080/09613218.2016.1102013

Marsh, R. (2017). Building lifespan: effect on the environmental impact of building components in a Danish perspective. *Architectural Engineering and Design Management*, *13*(2), 80–100. https://doi.org/10.1080/17452007.2016.1205471

Maslesa, E., Jensen, P. A., & Birkved, M. (2018). Indicators for quantifying environmental building performance: A systematic literature review. *Journal of Building Engineering*, *19*(March), 552–560. https://doi.org/10.1016/j.jobe.2018.06.006

Means, P., & Guggemos, A. (2015). Framework for Life Cycle Assessment (LCA) Based Environmental Decision Making during the Conceptual Design Phase for Commercial Buildings. *Procedia Engineering*, *118*, 802–812. https://doi.org/10.1016/j.proeng.2015.08.517

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

Mestre, A., & Cooper, T. (2017). Circular Product Design. A Multiple Loops Life Cycle Design Approach for the Circular Economy. *The Design Journal*, *20*, S1620–S1635. https://doi.org/10.1080/14606925.2017.1352686

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production*, *260*. https://doi.org/10.1016/j.jclepro.2020.121134

Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2

Nasir, M. H. A., Genovese, A., Acquaye, A. A., Koh, S. C. L., & Yamoah, F. (2017). Comparing linear and circular supply chains: A case study from the construction industry. *International Journal of Production Economics*, *183*, 443–457. https://doi.org/10.1016/j.ijpe.2016.06.008

Ness, D. A., & Xing, K. (2017). Toward a Resource-Efficient Built Environment: A Literature Review and Conceptual Model. *Journal of Industrial Ecology*, *21*(3), 572–592. https://doi.org/10.1111/jiec.12586

Niero, M., & Kalbar, P. P. (2019). Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. *Resources, Conservation and Recycling*, *140*(September 2018), 305–312. https://doi.org/10.1016/j.resconrec.2018.10.002

Niero, M., & Olsen, S. I. (2016). Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of aluminium cans with inclusion of alloying elements. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2016.06.023

Nußholz, J., & Milios, L. (2017). Applying circular economy principles to building materials: Front-running companies ' business model innovation in the value chain for buildings Applying circular economy principles to building materials : Front-running companies ' business model innovati. In *SustEcon Conference*. Berlin, Germany.

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

OECD. (2019). *Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences*. https://doi.org/10.1787/9789264307452-en

Ohms, P., Andersen, C. E., Rasmussen, F. N., Ryberg, M., Hauschild, M., Birkved, M., & Birgisdottir, H. (2019). Assessing buildings' absolute environmental sustainability performance using LCA focusing on climate change impacts. *IOP Conference Series: Earth and Environmental Science*, *352*(1). https://doi.org/10.1088/1755-1315/352/1/012058

Østergaard, N., Thorsted, L., Miraglia, S., Birkved, M., Rasmussen, F. N., Birgisdóttir, H., … Georgiadis, S. (2018). Data Driven Quantification of the Temporal Scope of Building LCAs. *Procedia CIRP*, *69*, 224–229. https://doi.org/10.1016/j.procir.2017.11.057

Pagoropoulos, A., Pigosso, D. C. A., & McAloone, T. C. (2017). The Emergent Role of Digital Technologies in the Circular Economy: A Review. *Procedia CIRP*, *64*, 19–24. https://doi.org/10.1016/j.procir.2017.02.047

Paleari, M., Lavagna, M., & Campioli, A. (2016). The assessment of the relevance of building components and life phases for the environmental profile of nearly zero-energy buildings: life cycle assessment of a multifamily building in Italy. *International Journal of Life Cycle Assessment*, *21*(12), 1667–1690. https://doi.org/10.1007/s11367-016-1133-6

Partners Circle House. (2018). *Circle House*. KLS PurePrint.

Pauliuk, S. (2018). Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2017.10.019

Pearce, D. W., & Turner, R. K. (1990). *Economics of natural resources and the environment*. London: Harvester Wheatsheaf.

Pieroni, M. P. P., McAloone, T. C., & Pigosso, D. C. A. (2019). Business model innovation for circular economy and sustainability: A review of approaches. *Journal of Cleaner Production*, *215*, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036

Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment – What does the evidence say? *Journal of Environmental Management*, *181*, 687–700. https://doi.org/10.1016/j.jenvman.2016.08.036

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment : A research framework. *Journal of Cleaner Production*, *143*, 710–718. https://doi.org/10.17863/CAM.7204

Pomponi, F., & Moncaster, A. (2019). Briefing : BS 8001 and the built environment: a review and critique. *Proceedings of the Institution of Civil Engineers – Engineering Sustainability*, *172*(3), 111–114.

https://doi.org/https://doi.org/10.1680/jensu.17.00067

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring innovation in the product chain. In *PBL Netherlands Environmental Assessment Agency*.

Rasmussen, F. N., Birkved, M., & Birgisdóttir, H. (2019). Upcycling and Design for Disassembly - LCA of buildings employing circular design strategies. *IOP Conference Series: Earth and Environmental Science*, *225*(1). https://doi.org/10.1088/1755-1315/225/1/012040

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

Rehberger, M., & Hiete, M. (2020). *Allocation of Environmental Impacts in Circular and Cascade Use of Resources - Incentive-Driven Allocation as a Prerequisite for Cascade Persistence*.

Reike, D., Vermeulen, W. J. V., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. *Resources, Conservation and Recycling*, *135*(August 2017), 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027

Remondis. (2020). Shortage of raw materials. Retrieved November 16, 2020, from https://www.remondis-sustainability.com/en/sharing/shortage-of-raw-materials/

Resch, E., & Andresen, I. (2018). A database tool for systematic analysis of embodied emissions in buildings and neighborhoods. *Buildings*, *8*(8). https://doi.org/10.3390/buildings8080106

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM : Visualization of environmental potentials in building construction at early design stages. *Building and Environment*, *140*(December 2017), 153–161. https://doi.org/10.1016/j.buildenv.2018.05.006

Röck, M., Ruschi Mendes Saade, M., Balouktsi, M., Nygaard, F., Birgisdottir, H., Frischknecht, R., … Lützkendorf, T. (2020). Embodied GHG emissions of buildings – The hidden challenge for e ff ective climate change mitigation. *Applied Energy*, *258*(June), 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, E. F. Lambin, … J. A. Foley. (2009). A safe operation space for humanity. *Nature*, *461*(September), 472–475.

Rønholt, J., Eberhardt, L., Birkved, M., Birgisdottir, H. & Bey N. (2019). Tracing the environmental impact origin within the existing building portfolio of prevailing building typologies. *Submitted to 1sr Nordic Conference on Zero Emission and Plus Energy Buildings*.

Rosenbaum, R. K., Georgiadis, S., & Fantke, P. (2018). Uncertainty Management and Sensitivity Analysis. In *Life Cycle Assessment: Theory and Practice* (pp. 271–321). https://doi.org/10.1007/978-3-319-56475-3_11

Ruuska, A. P. (2018). *Sustainability of builings - New perspectives on material-related environmntal impacts of builings*. 1–145.

Sanchez, B., & Haas, C. (2018). A novel selective disassembly sequence planning method for adaptive reuse of buildings. *Journal of Cleaner Production*, *183*, 998–1010. https://doi.org/10.1016/j.jclepro.2018.02.201

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, *229*, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019

Sathre, R., & González-García, S. (2013). Life cycle assessment (LCA) of wood-based building materials. *Eco-Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies*, 311–337. https://doi.org/10.1533/9780857097729.2.311

Scholten, N., & van Ewijk, H. (2013). Environmentla Performance Regulations in the Netherlands. *4th International Conference CIVIL ENGINEERING` 13 Proceedings*.

Schrijvers, D. L., Loubet, P., & Sonnemann, G. (2016). Critical review of guidelines against a systematic framework with regard to consistency on allocation procedures for recycling in LCA. *International Journal of Life Cycle Assessment*, *21*(7), 994–1008. https://doi.org/10.1007/s11367-016-1069-x

Sommer, J., & Guldager, K. (2016). *Building a Circular Future*. The Danish Environmental Protection Agency.

Sorrell, S. (2009). Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy*, *37*(4), 1456–1469. https://doi.org/10.1016/j.enpol.2008.12.003

Stahel, W. (1982). The product-life factor. In *An inquiry into the nature ofsustainable societies: The role afthe private sector,* edited by S. G. Orr, 72–96: The Woodlands, TX: HARC.

Tanikawa, H., Fishman, T., Okuoka, K., & Sugimoto, K. (2015). The weight of society over time and space: A comprehensive account of the construction material stock of Japan, 1945-2010. *Journal of Industrial Ecology*, *19*(5), 778–791. https://doi.org/10.1111/jiec.12284

Tingley, D. D., & Arbabi, H. (2017). The importance of understanding the material metabolism of the built environment. *World Sustainable Built Environment Conference 2017 Hong Kong Transforming Our Built Environment through Innovation and Integration: Putting Ideas into Action 5-7 June 2017*, (February), 888–894.

UN. (2020). *The sustainable development goals report 2016*. https://doi.org/10.29171/azu_acku_pamphlet_k3240_s878_2016

Urup, L. (2016). *Integrated Design-Build Management - Studying Institutional Processes to Understand Project Coordination & Performance Integrated Design-Build Management*.

Van Der Harst, E., Potting, J., & Kroeze, C. (2016). *Comparison of different methods to include recycling in LCAs of aluminium cans and disposable polystyrene cups*. https://doi.org/10.1016/j.wasman.2015.09.027

Van Stijn, A., & Gruis, V. H. (2019). Circular Housing Retrofit Strategies and Solutions: Towards Modular, Mass-Customised and "Cyclable" Retrofit Products. *IOP Conference Series: Earth and Environmental Science*, *290*(1). https://doi.org/10.1088/1755-1315/290/1/012035

van Stijn, A., Eberhardt, L. C. M., Wouterszoon Jansen, B., & Meijer, A. (2020). Design guidelines for circular building components based on LCA and MFA. *Submitted to Journal of Cleaner Production*.

van Stijn, A., & Gruis, V. (2019). Towards a circular built environment: An integral design tool for circular building components. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-05-2019-0063

Vogtländer, J. G., Baetens, B., Bijma, A., Brandjes, E., Lindeijer, E., Sergers, M., & Witte, F. (2010). LCA-based assessment of sustainability: the Eco-costs/Value Ratio EVR. In *Delft University of Technology, Nederland*. Delft: VSSD.

Westerholm, N. (2020). *State of Play for Circular Built Environment in Europe*.

Winkler, H. (2011). Closed-loop production systems - A sustainable supply chain approach. *CIRP Journal of Manufacturing Science and Technology*, *4*, 243–246. https://doi.org/10.1016/j.cirpj.2011.05.001

Wohlin, C. (2014). Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Procceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering - EASE '14. ACM Press, New York, USA*, 1–10. https://doi.org/10.1145/2601248.2601268

Wolf, M., & Chomkhamsri, K. (2014). *The " Integrated formula " for modelling recycling , energy recovery and reuse in LCA White paper*. Retrieved from http://maki-consulting.com/wp-content/uploads/2013/05/White-paper-Integrated-approach_Wolf&Chomkhamsri2014_Final.pdf

Worldbank. (2018). *What a waste 2.0: A Global Snapshot of Solid Waste Management to 2050*.

Wouterszoon Jansen, B., van Stijn, A., Gruis, V., & van Bortel, G. (2020). A circular economy life cycle costing model (CE-LCC) for building components. *Resources, Conservation and Recycling*, *161*(December 2019), 104857. https://doi.org/10.1016/j.resconrec.2020.104857

Yamada, H., Daigo, I., Matsuno, Y., Adachi, Y., & Kondo, Y. (2006). Application of Markov chain model to calculate the average number of times of use of a material in society: An allocation methodology for open-loop recycling - Part 1: Methodology development. *International Journal of Life Cycle Assessment*, *11*(5), 354–360. https://doi.org/10.1065/lca2006.05.246.1

Yin, R. K. (2003). Case study research: Design and Methods. In *Sage Publication Ltd.* (5th ed.). Retrieved from https://doc1.bibliothek.li/acc/flmf044149.pdf

Zampori, L., & Pant, R. (2019). Suggestions for updating the Product Environmental Footprint (PEF) method. In *JRC Technical Repports*. https://doi.org/10.2760/424613

Zimmermann, R. K., Andersen, C. E., Kanafani, K., & Birgisdóttir, H. (2020). *Sbi 2020:04*.

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, *21*(3), 593–602. https://doi.org/10.1111/jiec.12545

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