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Informing architectural design processes in a circular economy - the quantification of circular construction

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Preface

This thesis summarizes the work and results of the PhD project 'Informing architectural design processes in a circular economy - the quantification of circular construction', which was carried out at DTU (the Technical University of Denmark) from 2019 to 2023. The thesis is inextricably linked with the EU Horizon project CIRCuIT, which has both contributed the majority of the funding and provided the data for the project through case studies and extracts from databases. The theoretical part of the PhD project started at DTU in December 2019 in the section for Design and Processes with Associate Professor Lotte Bjerregaard Jensen (former DTU Civil Engineering) as main supervisor and Assistant Professor Morten Ryberg (former DTU Management) as co-supervisor. A change in the supervisor team in the autumn of 2022 has resulted in the PhD being completed in the section for Materials and Durability with Professor Lisbeth M. Ottosen (DTU Environmental and Resource Engineering) as main supervisor and Professor Lotte Bjerregaard Jensen (Aarhus School of Architecture) and senior sustainability specialist Morten Ryberg (SWECO) as co-supervisors. In addition, some of the work has also been conducted in Hamburg during a three-month research stay at the Hamburg University of Technology (Sustainable Resource and Waste Management) in the spring of 2022. This was partly made possible with a travel grant from the Knud Højgaard Foundation.

In addition to the scientific contribution to the articles and this thesis, this PhD project has also contributed to communication and teaching at DTU through the supervision of five bachelor's thesis students and seven master's thesis students, as well as the teaching of LCA (Life-cycle assessment) on the sustainability courses for civil engineering students at DTU.

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I want to express my deepest gratitude to Professor Lotte Bjerregaard Jensen, who was my main supervisor throughout most of my PhD. Without Lotte's support, guidance, and faith in me, this PhD project would never have been possible. Also, a special thanks to Professor Lisbeth Ottosen for taking over the task as my new main supervisor at the end of my PhD and supporting me in the writing of the thesis. I would also like to thank my co-supervisor Morten Ryberg for scientific sparring about ideas and feedback on articles. My collaboration with Associate Professor Kristoffer Negendahl, has also been a great support in carry out analyses and publishing articles. I would therefore like to acknowledge Kristoffer for all the time he has invested in my scientific development and my project.

This PhD has been purely theoretical so without data, it would not have been possible to carry out the analyses. Special thanks and gratitude must go to all the external partners who have provided data or helped with database extracts. I would therefore like to thank Thor Nyborg Bendsen, Emil Møller Rasmussen, and Andrew Simmons from Copenhagen Municipality, Tim Riis Tolman from Lendager, Rasmus Krag from Tscherning, Nichlas Moos Heunicke from 3XN and Signe Bang Korsnes from Arkitema. In addition, I would also like to thank the CIRCuIT partners Martin Tilsted & Frederik Fenger Petersen from Copenhagen Municipality, and Anne-Mette Manelius from Vandkunsten for their support and cooperation. I would also like to thank Regitze Kjær Zimmermann from Aalborg University for answering questions from my students and me about LCABYG. In addition, several study projects have also contributed to my PhD project. I would therefore also like to thank my former students Eva Neel Bacher, Maria Wiksell Tram, Anders Stokbro Ravn, Nanna Reichert Borch Larsen, Mathias Emil Steuch, Karen Vase Langballe, Mikkel Toke Brivio Volden, Frederik Brauer, Lasse Bækgaard Schytte, Alina Barun, Tomislav Martinović and Kin Sun Tsang for their essential contributions.

Finally, I want to thank my family and friends for their unconditional support, interest in my work, and great understanding during periods when the PhD has taken up most of my time.

Abstract

The construction sector contains great potentials to contribute to our society's green and circular transition since the construction sector is responsible for the emission of 40% of all greenhouse gases and produces 40% of the waste generation. Several political initiatives have been adopted in recent years to accelerate a sustainable transition of the construction sector, such as the European Green Deal from 2020 and the introduction of Danish requirements for CO_2 limits and mandatory LCA calculations for new construction from 2023. However, the transition occurs very slow and large scale applied circular and sustainable principles are still only represented in very few buildings. Therefore, there is a need to generate more knowledge and awareness about the potentials for implementing circular economy in both new construction and in the existing building stock. Through case studies, data mappings, analyses, and collaborations with industry and public administration, this project has investigated the circular potential in the existing building stock by focusing on demolitions, lifespans, and circular design strategies.

Through data mapping, several Danish registers for building data were identified. The data mapping showed that there is generally little knowledge about the material composition of the existing building stock. The material composition of Danish building typologies was investigated by collecting pre-demolition audits submitted to the municipality, which were analysed via material flow analysis. However, it turned out that the data quality of the pre-demolition audits was too low to determine the material composition, so it was impossible to make accurate material estimates for similar building typologies based on the current data. Thus, an alternative parametric model was tested based on data from historical typology studies of the most commonly used building parts in existing buildings. A comparison showed that the parametric model could provide more accurate material estimates if extensive typology studies were available. In addition, the parametric model could also generate a 3D model that can be used for verification, visualization, and future analyses on existing buildings.

Demolition data was obtained on more than 120,000 demolition cases over ten years from one of the identified registers in the data mapping. An analysis of the demolition data was carried out in order to examine demolition patterns and the lifespan of existing buildings. These analyses showed that mainly industrial buildings are demolished and replaced with housing. A study of the lifespans of newer industrial buildings also showed that newer office buildings will have a shorter expected lifespan than older office buildings. This was a general trend for most building types, where the expected average lifespan is longer for old buildings than for new buildings. In addition, a comparison of demolition patterns in Denmark and the Copenhagen region showed that newer buildings in Copenhagen were demolished more often than in rest of Denmark where older buildings are most often demolished.

A comparison of new construction and demolition showed that 5-6 times more square meters are built than are demolished, which significant limits how much circular materials from demolitions can replace

in new construction. There is, therefore, also a great need to focus on flexible waste prevention strategies such as refurbishment and transformations that can reduce the need for new construction.

Although circular materials can only cover a small part of our need for new materials, there are significant environmental and climate benefits from circular reuse, which was demonstrated in this project through a comparative LCA study of selective demolition with subsequent preparation for the reuse of steel facade panels as was compared to conventional demolition with subsequent recycling of the steel. Here the result showed that across all environmental categories, there was a saving by reusing rather than recycling and that the reuse scenario resulted in a CO_2 saving of around 40%. Still, there is generally a lack of much more evidence in order to confirm whether this applies to all materials and what significance the use of circular materials and components in new buildings will have on the overall environmental impact.

Resume

Byggeriet indeholder store muligheder for at biddrage til både den grønne og cirkulære omstilling af vores samfund, eftersom at byggeriet udleder 40 % af alle drivhusgasser, og producere 40 % af alt affald. Der er inden for de seneste år blevet vedtaget flere politiske initiativer til at accelerere en bæredygtig omstilling af byggeriet, som fx, den Europæiske Green Deal fra 2020 samt introduktionen af Danske krav i 2023 med CO_2 grænser for større bygninger og udførelse af LCA beregninger for alle nye bygninger. Den reelle omstilling af byggeriet går dog langsomt, og gennemgribende cirkulære og bæredygtige principper er stadig kun repræsenteret i et fåtal af bygninger. Der er behov for mere viden omkring potentialerne for at implementere principper for cirkulær økonomi i byggeriet både for nye bygninger men også for den eksisterende bygningsmasse. Dette projekt har igennem case studier, dataudtræk, analyser og samarbejder med industrien og den offentlige administration kortlagt de seneste tendenser og potentialer i den eksisterende bygningsmasse inden for nedrivning, levetider og cirkulære designstrategier.

Gennem en omfattende data kortlægning blev der identificeret flere danske databaser indeholdende store mængder bygningsdata. Data kortlægningen viste at der generelt er meget lidt viden om materialesammensætningen i den eksisterende bygningsmasse, og der mangler, et overblik over hvilket muligheder de eksisterende materialer har for at indgå i fremtidige cirkulære processer. I et forsøg på at kortlægge materialesammensætningen af den danske bygningsmasse, blev der igennem Københavns Kommune udtrykket materialedata fra indmeldte nedrivningssager, som blev analyseret via materiale flow analyse. Det viste sig dog, at kvaliteten af dataene generelt var lav, og at det derfor ikke var muligt at lave retvisende materialeestimater på baggrund af den nuværende data. En alternativ parametrisk model blev derfor afprøvet hvor at datagrundlaget i stedet var historiske typologistudier, som beskriver de mest anvendt konstruktionsopbygninger og anvendte bygningsdele for forskellige byggeperioder. En sammenligning viste, at den parametriske model kunne give mere præcise materiale estimater hvis der var omfattende typologistudier tilgængelig. Derudover kunne der også genereres en 3D model som kan anvendes til verificering, visualisering og til fremtidige cirkulære analyser på eksisterende bygninger.

Fra en af de kortlagte databaser blev der indhentet data på mere end 120.000 nedrivningssager over en tiårig periode. Gennem en analyse af de nedrevet bygninger blev der skabt ny viden omkring nedrivningsmønstre, levetider og cirkulære potentialer i eksisterende bygninger. Analyserne viste at det hovedsageligt er industribygninger der bliver nedrevet som efterfølgende bliver er erstattet med boliger. En analyse af levetiderne af nyere industribygninger viste, at nyere kontorer i fremtiden kommer til at have en kortere forventet gennemsnits levetid end ældre kontorbygninger. Dette var en generelt trend for de fleste bygningstyper hvor at den forventede gennemsnitlige levetid er længere for gamle bygninger end for nyere bygninger. Derudover viste en sammenligning af nedrivningsmønstre i Danmark og for Københavns området, at nyere bygninger i København oftere bliver nedrevet, hvorimod

at det oftere var ældre bygninger som blev nedrevet i resten af Danmark. En sammenligning af nybyggeri og nedrivning viste, at der bliver bygget 5-6 gange flere kvadratmeter end der bliver nedrevet, hvilket er en stor begrænsning for, hvor meget cirkulære materialer fra nedrivninger kan erstatte af materialebehovet i nybyggeri. Der er derfor også i stor grad behov for at fokusere på fleksible affaldsforbyggende strategier som renoveringer og transformationer, som kan nedbringe behovet for nybyg.

Selvom at cirkulære materialer kun kan dække en mindre del af vores behov for nye materialer, er der på komponent niveau store miljø og klimamæssige gevinster ved at genbruge. Dette blev demonstreret gennem et komparativt LCA studie af selektiv nedrivning med efterfølgende klargør til genbrug af stålfacadeplader, som blev sammenlignet med konventionel nedrivning med efterfølgende genanvendelse af stålet. Her viste resultatet, at der på tværs af alle miljøkategorier var en besparelse ved at genbruge fremfor at genanvende, og at genbrugsscenariet resulterede i en CO_2 besparelse på omkring 40 %. Dette demonstrere at det kan være miljømæssige fordelagtigt ved at genbruge fremfor at genanvende, men der mangler generelt meget mere evidens gennem flere studier af genbrug, for at kunne fastslå, om dette gælder for alle materialer, samt hvilket betydning anvendelse af cirkulære materialer og komponenter i nye bygninger, vil have på den samlede miljøpåvirkning i byggeriet.

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List of Abbreviations

3D	-	Three-dimensional
3R	-	Reduce, reuse and recycle
9R	-	Refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose and recycle
AHP	-	Analytic Hierarchy Process
AI	-	Artificial intelligence
BBR	-	Bygnings- og Boligregistret
BIM	-	Building Information Modelling
BREEAM	-	Building Research Establishment Environmental Assessment Method
C&D	-	Construction and demolition
CE	-	Circular economy
CIRCuIT	-	Circular Construction in Regenerative Cities
CO2	-	Carbon dioxide
CP	-	Conference paper
DCFA	-	Discounted Cash Flow Analysis
DGNB	-	Deutsche Gesellschaft für Nachhaltiges Bauen
EU	-	European Union
FBB	-	Fredede og Bevaringsverdige Bygninger
GDPR	-	Survey of Architectural Values in the Environment
GHG	-	Greenhouse gases
GIS	-	Geografic Information System
GPS	-	Global Positioning System
JP	-	Journal paper
LCA	-	Life-cycle assessment
LEED	-	Leadership in Energy and Environmental Design
MCDA	-	Multi-Criteria Decision-Aiding
MCDM	-	Multi-Criteria Decision-Making
PCB	-	PolyChlorinated Biphenyl
PROMETHEE	-	Preference Ranking Organization Method for Enrichment of Evaluations
SAVE	-	Survey of Architectural Values in the Environment
TOPSIS	-	Technique for Order of Preference by Similarity to Ideal Solution
WP	-	Work package

Structure of the Thesis

This thesis is divided into seven chapters that outline the research carried out during the three-year PhD project. The content of the three main chapters is based on the combined work that the author has published in four scientific journal articles and two full-length conference articles during the PhD. The content of the respective chapters is as follows:

1. **Introduction:** Present an overview of the background to the PhD project and an up-to-date status report on the current conventional construction sector and the transition to a circular construction sector.

2. **Knowledge gaps and barriers in circular construction:** Describe and outline the knowledge gaps and barriers that have been identified in circular construction, which has formed the focus of this PhD project.

3. **Research Methodology:** Present the research methods used to form the overall structure of the project. Some of the specific research methods used during the project are described in detail in the appended papers.

4. **Main, part 1 - Mapping the available data on the existing built environment and material stocks in cities:** Focus on identifying existing building and materials data that can be used for both micro-, meso- and macro-scale analyses of refurbishment potentials in existing buildings. Describe how publicly available building registers have been established and how their quality can be improved.

5. **Main, part 2 - Trends in the demolition and life-cycles of buildings:** Investigate developments in historical demolition patterns for different building uses and construction periods through data identified in Part 1. This is allows a better understanding of the dynamic life-cycles of existing buildings through better lifespan predictions for historic building typologies. Finally, how conventional demolition can be improved through circular material-handling from future selective demolitions is investigated.

6. **Main, part 3 - Assessment of circular design strategies:** Develops and tests analytical tools and methods for assessing and visualizing the transformation potentials of existing buildings and the potential environmental benefits of applying circular design strategies such as reuse of building components.

7. **Main conclusions:** Summarize all the main conclusions from the three main chapters in relation to the identified knowledge gaps.

1. Introduction

One of humanity's most significant challenges is to reduce the large emission of CO_2 that causes climate changes due to global warming. At the COP21 conference in 2015, most countries agreed to reduce temperature rises to below 2°C above pre-industrial levels, which was later tightened to a maximum of 1.5°C by the end of this century. However, the UN's latest estimate is that the temperature increase based on current policies will be around 2.6°C to 2.8°C [1] by the end of this century. Construction is one of the largest emitters of CO_2, with a share of 40% of all human-origin CO_2 emissions. About two-thirds of CO_2 emissions in construction come from the operation of buildings, and one-third from the production of materials and building components. With a growing global population, increasing urbanization and the increased demand for good-quality housing [2], construction is an extremely important focus in reducing resource consumption, CO_2 emissions and impacts on the environment. Because construction generates 40% of all global waste, applying circular waste-management principles such as reuse and recycling can help reduce the need for new materials and reduce CO_2 emissions from the production of new products. In addition, 75% [2] of the housing stock in Europe was built before 1979 and therefore needs maintenance. Along with maintenance, there is also a need to lower the energy consumption of existing buildings by saving CO_2 through better insulation and energy efficient installations, as well as converting operating energy away from fossil-fuel energy sources such as oil and gas to renewable energy systems based on district heating and heat pumps. In addition to the fact that a circular transition is necessary, this is also an opportunity for further the development of our society, where the EU expects that a circular transition in 2030 will be able to create 700,000 new jobs and increase the EU's annual GDP by 0.5% [3].

Energy requirements in construction in Denmark were introduced in the building regulations in 1961 and tightened in 1972 due to the oil crisis of the 1970s. Subsequently, the requirements for energy have been tightened several times during the last fifty years, with stricter requirements for U-values and the technical characteristics of installations. However, previously the focus has been on the energy part via energy classes and not on the material aspect of construction. This changed in early 2020 [4] when an addition to the Danish building regulations regarding sustainability classes in construction was presented in the Danish National Strategy for Sustainable Construction. From 2023, therefore, it will be a requirement that new buildings over 1000 m^2 can emit a maximum of 12 kg CO_2/m^2/year. These requirements are continuously tightened every second year so that the CO_2 limit in 2029 will peak at 7.5 kg CO_2/m^2/year for all new buildings. In addition, requirements will also be introduced for LCA calculations to be performed on all new buildings. Also at the EU level, a lot has happened politically within sustainable and circular construction in recent years, especially with the introduction of the European Green Deal from 2020, which sets a target for reducing CO_2 emissions by 55% in 2030 and later to make the EU climate-neutral by 2050 [5]. Specifically for buildings, the European Green Deal also has a strategy to create more energy and resource-efficient buildings through the A Renovation

Wave for Europe strategy. With its "energy efficiency first" principle, this strategy has a greater focus on reducing energy consumption, implementing more renewable energy, and improving energy affordability for medium and lower income households, rather than on specific circular measures [6].

The Danish government's circular economy strategy from 2018 [7] also has the ambition of implementing selective demolition in construction in order to promote more circular forms of waste-management from demolitions with a focus on the reuse of building materials, as well as an initiative on the use of bio-based materials. So far, the implementation of actual circular initiatives other than a revision of legislation on waste is lacking, and the political strategies on circular economy in construction have therefore mainly resulted in various preliminary studies of, for example, materials passports [8] and the potentials for reuse and recycling [9]. The circular economy is one of the major focal points in the European Green Deal, which led to the formation of the Circular Action Plan, with initiatives around a revision of the Construction Product Regulation and a revision of the material renovation target for construction and demolition waste. In addition, there will also be a focus on improving the durability and adaptability of buildings and also on developing digital logbooks for storing data about buildings [10].

With the increased focus and the many initiatives within the circular economy in construction, it is important to create an understanding of the underlying dynamics and trends in construction that can have an influence on how many environmental or sustainability benefits can be obtained from a circular transformation of the construction industry. The aim of this PhD thesis is to determine the current status of the foundation for circular construction by performing in-depth data analyses on the existing building stock and collecting new data on demolition patterns, materials in buildings and circular demolition. These findings will be used to establish methods for the quantification of circular construction, which together with the new collected data can support architectural design processes in order to choose the optimal building adaptation strategy in a circular economy.

1.1. What is circular construction?

Circular construction is the application of the principles of the circular economy in the construction industry. The aim of circular construction is to circulate the materials within the value chain and thereby keep their value as high as possible for as long as possible through maintenance, reuse and recycling. The opposite of a circular construction industry is a linear construction industry where waste is typically sent to landfill or disposed with very small environmental benefits. Although reuse and recycling have existed for over a millennium (e.g. in old half-timbered buildings), the more theoretical part of the circular economy originates from the concept of industrial ecology from the 1970s [11]. Industrial ecology focuses on studying industrial systems with the aim of reducing their consumption of natural materials and their generation of waste. There is much debate about where and by whom circular thinking was first suggested, but many point to Kenneth Boulding as one of the inventors of circular thinking with his definition: *"one must find his place in a cyclical ecological system which is capable of continuous reproduction of material form, even though it cannot escape having inputs of energy"* [12]. Around the 1980s, several theories were created around the principles known as the 3 'R's (reduce, reuse and recycle; as in [13]) which are very similar to the definitions we use for circular economy today, with the difference that the EU has now expanded the 3R principles to 9R (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose and recycle) [14]. However, the term 'circular economy' was really popularized by the Ellen MacArthur Foundation in 2012, which also introduced the butterfly diagram for circular flows in technical and biological cycles and the Chinese Circular Economy Promotion Law in 2009 [15]. Today, the circular economy is a very widespread concept and is used in many different contexts with sustainability, as shown by the fact that there now are over 114 different definitions of 'circular economy' [16]. However, it is important to mention that the circular economy must be seen as a condition for or a tool of sustainability [17] and therefore does not constitute actual proof of sustainability. There are therefore some who criticize the notion of the circular economy for being too focused on the economics and thereby omitting or simplifying the environmental and social consequences or benefits [18]. Among the positive socially derived effects of a switch to a circular economy is the creation of new job opportunities, while the positive environmentally derived effects include the reduced consumption of virgin materials, reduced waste, and lower CO_2 emissions [19] through circular R principles.

1.2. Circular waste-handling of materials and components

As described in section 1.1, reducing, reusing and recycling C&D (construction and demolition) waste are among the initiatives that inform the circular restructuring of construction. The main purpose is to keep the highest possible value of the material for as long as possible in all of its life stages. The best strategy in relation to the environment is to reduce the amount of waste that is generated from construction by maintaining building components to ensure they are in a good condition, which then leads to a reduced risk of them becoming construction waste. This principle of avoiding creating waste can happen on both the component and building level and is often referred to as lifespan extension, which can be achieved through refurbishment or adaptive reuse strategies.

1.2.1. Construction and demolition waste in Denmark

In demolition, it often happens that materials such as concrete, bricks, and asphalt are crushed and used as a substitute for gravel in roads, or as a base layer or backfill on construction sites. In Denmark in 2017, the recycling rate of C&D waste was 85% [20], but after the characterization of C&D was changed to conform to the EU's waste hierarchy [21], in 2018 the recycling rate fell to 37% [22], whereas 52% of C&D is now labelled as 'other type of utilization'. The remaining material-handling options in the waste hierarchy with the lowest value are typically incineration and landfill. Incineration of waste can be optimized by producing district heating and electricity, which is commonly used in

Denmark, where 6% of all C&D waste and 51% of all household waste was incinerated in 2018 [22]. Only a very small part of the total C&D waste ends up as landfill in Denmark (around 5-6%) [23], whereas in some EU countries, such as Romania, Bulgaria and Montenegro, landfill makes up over 90% of all their waste management. Across the entire EU, the share of landfill together with other types of disposal is around 45% [24] of all handled waste. In Denmark, construction generates around 5 million tonnes of C&D waste annually [25], of which concrete and asphalt make up the largest part, responsible for a quarter each of total C&D waste production. Another large C&D waste category is the mixed fractions of different waste, which also make up about a quarter of total C&D waste. The last quarter of C&D waste thus consists of sorted metals, plastics, glass, wood, insulation and plaster materials. In comparison with the annual five tons of C&D waste generation in Denmark, China produced around 1.13 billion tons of C&D waste in 2014 [26]. With a rapidly increasing middle class in China, it can be expected that there will be more construction activity and that waste production will therefore increase. C&D waste can come from demolition, renovation or replacements, or from losses in the construction process. However, while there are annual estimates of the total amount of C&D waste, there is very little knowledge on which buildings are demolished in Denmark and how the total amount of C&D waste is distributed across different building typologies and construction periods. This is important in being able to predict which materials will be demolished in the future and which types of materials will become available for circular material flows.

1.2.2. Waste from demolitions of existing buildings

In 2020 Denmark’s C&D waste was equivalent to 40% of the country’s total generated waste [23]. No distinctions are made in the waste statistics about the origin of the waste, so at present there is no data on how the five million tonnes of C&D waste is distributed between demolitions, renovations and new constructions. The reason why it is relevant to separate waste from demolition from waste from new construction is that the types of waste differ significantly because waste from demolition consists of materials that have historically been used in construction (bricks, wood, ceramics, glass, concrete), whereas waste from new construction consists of materials that are currently used (concrete, plastic, steel, aluminium) [27]. Demolition waste from old buildings can also contain harmful substances which can reduce the opportunities for circular use [28] because waste regulations in the EU currently focus on reducing the dispersal of hazardous substances in waste rather than the circulation of materials [29]. The annual waste statistics are based on data from waste treatment sites, and there is currently no traceability in relation to how the generation of waste is distributed among different sources. Better data on demolition waste can be obtained by combining data from reliable structured pre-demolition audits with stock modelling of buildings that may be demolished in the future [30]. However, many countries have neither reliable data on demolition waste from pre-demolition audits nor waste statistics. Material or waste data is fundamental to be able to create successful waste-management plans, so a large number of studies have been performed in recent years with the ability to develop methods for quantifying construction and demolition waste [31]. Although there has been a major development in methods for assessing waste quantities, a prerequisite for more reliable estimates is that more research is conducted into the data and assumptions that underlie the waste estimates [32].

1.2.3. Waste from new construction

In the past, there has not been much focus on waste production on construction sites, which is the reason why many construction companies have not previously had a strategy to minimize waste [33]. The generation of waste in new construction can be caused by several factors, but among the five biggest reasons are mistakes in ordering components, damaged packaging, design errors, material cut-offs and components damaged by weather [33,34], after which they are discarded and replaced. This will therefore lead to an increased generation of waste, as well as an increased demand for new materials. Previous studies have estimated that around 1-10% [35] of the materials that enter a building site leave the building site as waste before the building is in use. However, more recent studies from China estimate that the losses may be even higher for some materials, where timber formwork in connection with concrete can have waste rates of 80% on construction sites [36]. To minimize the generation of waste in the construction process, it is important to implement a material control strategy that includes educating construction workers in correct material handling [34,37], the timely communication of design changes to the building [33], GPS (Global Positioning System) or GIS (Geografic Information System) integrated solutions for better monitoring [38], prefabrication [39], legislation [40] and the use of standardised building components [33,37,41]. Implementing more prefabrication is also one of the most effective methods of reducing the amount of waste in new construction [42]. At the same time, it is also important to maintain a focus within the material control strategy on reducing the loss of materials throughout the entire construction period, since two-thirds [43] of the waste from construction sites is generated during the last steps of the construction period.

1.2.4. Circular recycling and reuse of materials from construction waste

There are three dominant factors which determine the options for recycling waste: economy, compatibility with virgin materials, and the material properties of the waste materials [44]. The economic factor should ensure that a product produced with reused or recycled materials can compete economically or demand wise with products based mainly on virgin materials. The compatibility of the waste product determines whether it is technically possible to combine the product with other materials to produce new products. In addition, it is important that the addition of recycled materials does not compromise the technical properties of the new product and therefore decrease its quality compared to new products or implement hazardous substances. Reuse of building components is not widespread in the construction industry today, but, despite planning, legal, knowledge and financial challenges, some projects have demonstrated that it is technically possible to use reused components [45] in new construction. One of the most common methods of handling C&D waste is crushing to produce aggregate for lower-grade applications [44] as a base layer for roads or construction sites. Crushing is used in particular for the large amount of concrete and bricks that is the main C&D waste fraction in western Europe [46]. Glass and metals are typically remelted and thereby replace high-value virgin materials. Plastics, cardboard and paper are either burned to generate energy or made into granules and used as a supplement in new plastic, cardboard and paper products [44].

One of the major advantages of reuse and recycling is the potential environmental savings in relation to both CO_2 and to reducing the consumption of virgin materials. Because reuse and selective demolition is still a niche activity, more documentation on the environmental impacts and costs of selective disassembly processes is lacking [47]. In addition, there is a lack of studies concerning the selective deconstruction programming for buildings, which means that there are currently very large uncertainties about the time consumption for the selective deconstruction of building components for reuse or in adaptive reuse processes [48]. LCA studies of end of life scenarios for building materials show that environmental savings follow the waste hierarchy, where reuse provides the highest environmental savings and that even low-grade recycling is still better than landfill [46]. However, the majority of LCA studies on waste management focus on household waste, and there is generally a large lack of LCA studies on the handling of C&D waste or on waste-prevention strategies [49]. One Chinese study has shown that recycling a ton of construction waste generated in Shanghai can result in a CO_2 saving in the magnitude of 100 kgCO_2e a ton of construction waste, where the biggest CO_2 saving comes from the recovery and recycling of steel [50]. Given our current environmental calculation methods in the construction industry, the difference in the calculated environmental impact between disposal and recycling is relatively small from the point of view of the waste producer, but very large from the point of view of the materials producer [51]. It is therefore important that LCA studies of recycling components use a life-cycle approach that includes all processes and external factors in the calculation [52]. An example of a process in recycling that can have a large impact on the overall potential savings through recycling is the transporting of waste, which can mean that recycling has a much higher environmental impact than reuse [53]. Limiting the distance to waste-sorting and recycling facilities is therefore important for the potential environmental savings from recycling [54].

In addition to the environmental benefits, there can also be financial benefits from recycling. High prices for virgin materials and taxes on waste can cause the total price of circular building components to fall proportionally to the proportion of recycled materials [55]. One method of promoting the share of recycling in new building components is through subsidies for circular components. Here, the most efficient method of ensuring the highest proportion of recycling is to subsidise the production of the building component rather than its purchase [56]. Increasing the costs of disposing of construction waste does not lead to an increased implementation of recycling either [57]. An important prerequisite for recycling to be economically profitable is to ensure the highest possible recovery rate of recyclable materials from the C&D waste [58]. Much of the foundation for a successful recycling process is therefore to ensure efficient sorting processes with a high recovery rate at both the demolition site and at the waste-management facility.

1.3. Circular building adaptation strategies

Renovation, remodelling, transformation and conversion in adaptations of existing buildings – there are many terminologies that cover different types of adaptation strategy for existing buildings, partly because there is a lack of clear definitions in both the academic and construction literature [59]. This section will therefore examine the state of the art of building adaptation strategies for existing buildings.

1.3.1. Terminology for building adaptation projects

In general, there are two main categories of building adaption for existing buildings, refurbishment and adaptive reuse. Both main categories can also be divided into several subcategories, which are more specific types of building adaptation strategy. The biggest difference is that there is a change in the building's function with adaptive reuse, whereas refurbishment preserves the original function of the building. This means that an existing office building may well be used for housing after an adaptive reuse, whereas it will continue to be used for offices if it has been refurbished. There are no clear definitions of what the various terms within the building adaptation projects cover, and therefore the literature and the professionals often use the terms differently, which can lead to confusion and misunderstandings. Many other terms have also been used in the past for refurbishment, such as enveloping, reinstatement, refitting, repair, restyling, overcladding or upgrading [59]. To avoid conceptual confusion, this PhD project will use the terminologies as defined and framed by the author in Figure 1. In reality, building adaptation projects are very complicated, and therefore several building adaptation principles may be carried out on the same building, making it impossible to come up with a precise division that covers all existing buildings. Most of the terminologies are based on the study by Sheida Shahi, who has made one of the largest mappings of terminologies related to building adaptation projects [60]. In that framework there are three refurbishment strategies: retrofitting, rehabilitation and renovation. However, these three concepts all contain some form of improvement. For existing buildings there is therefore a lack of concepts for the regular maintenance of building parts that are not broken (conservation) and for the refurbishment strategy for historic and listed buildings where the building is brought back to a previous state typically due to the preservation of its architectural or historical value (restoration). Vertical or horizontal additions to existing buildings are defined in [60] as a conversion strategy under adaptive reuse, but since the extension itself did not really have a function before the building's adaptation because it did not exist, it cannot be a question of a change of function. Extensions are therefore designated as a refurbishment strategy in Figure 1 and are referred to under the term 'remodelling'.

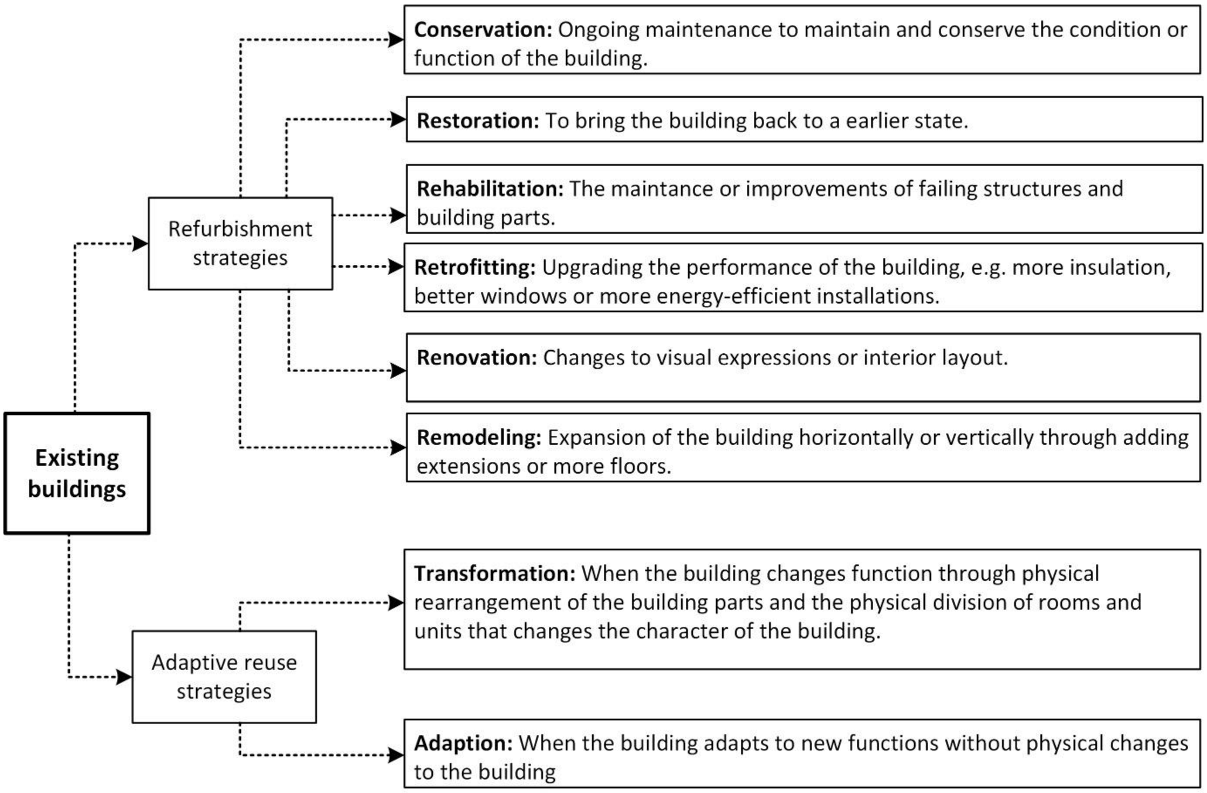

Figure 1. Terminologies and their categorical division used throughout this PhD thesis for different types of building adaptation project.

There is a greater difference in how different studies use the term ‘adaptive reuse’. In general, the adaptive reuse of existing buildings is the term for a change in function in order to preserve as much of the original building as possible and thereby avoid demolition. In the framework defined by [60], material reuse is a subcategory of adaptive reuse, but if the materials are reused on site without a change in function it is actually a refurbishment strategy. Similarly, if they are reused off site it is a demolition strategy (selective demolition), whereas materials will always be reused by a common conversion project within adaptive reuse, and therefore a division of the two concepts will not make sense. Reuse and recycling are therefore possible derived effects of building adaptation projects when materials and components are removed from the existing building. In this project, adaptive ‘reuse’ is shared by two terms, where transformation covers a change of function through physical changes to the building, and adaptation denotes functional changes in a building without major physical changes to it.

1.3.2. Refurbishment of existing buildings

Refurbishment strategies are the most common type of building adaptation to be carried out on existing buildings. A study from Stockholm has shown that buildings constructed between 1946 and 1975 have the highest potential for reducing CO_2 emissions in the building sector through refurbishment, estimating a potential reduction of the total energy consumption for building operations in Stockholm of 33% [61], since buildings from that period are poorly insulated and thereby have a high energy demand. 70% of the existing building stock (See Figure 2) in Denmark was constructed before 1979

[62], and since Danish energy requirements were first introduced in construction in 1961 [63], with a tightening of the requirements in 1972 [64], it can be assumed that similar energy savings can be achieved in Denmark. A future warmer climate as a consequence of large-scale emissions of GHG (greenhouse gases) will also provide heating savings by reducing the heating demand for existing buildings [65], but an increased need for mechanical cooling will offset any potential energy savings for the entire building stock [66,67]. A new Danish study has estimated that the annual CO_2 savings could be 1,083,000 tonnes a year if all existing buildings in Denmark were renovated. If the same buildings were also converted away from oil and gas to district heating and heat pumps, a total saving of 2,320,000 tonnes CO_2/year can be achieved [62].

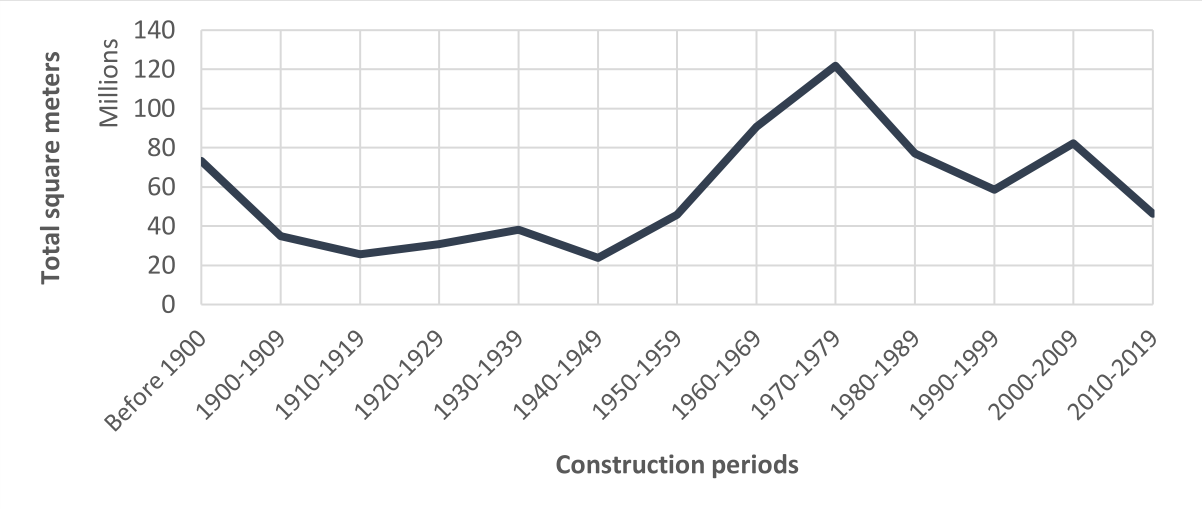

Figure 2. Total remaining building area in 2019 for different construction periods based on data from [68].

In recent years the introduction of analytical tools such as LCA has changed the focus in refurbishing decision-making from an operational perspective to a life-cycle perspective, including the impact of materials [69]. Many studies indicate that the environmental impact of materials can be reduced by extending their lifespan through building adaptation strategies rather than by building new, but that the very low energy consumption in new construction often generally offsets the environmental gain of refurbishment compared to new construction [70]. Therefore, the climate impact of refurbishment over time can be of the same order of magnitude as the climate impact of low-emission new construction in Denmark [71]. It is therefore important that in assessing building refurbishment options for existing buildings, there is a focus on bringing the building's technical condition up to existing energy and indoor climate requirements [72]. Developing decision-support tools to choose the best refurbishment strategy can be an incredibly complex process that often involves several different actors [71]. Tools for refurbishment decision support should be adaptable to the local perspective, since conditions, needs and problems may differ for country to country, and even from area to area [69]. Here local databases are essential for providing precise data for refurbishment decision support [69]. These decision tools should also include information on all six dimensions in refurbishment projects, namely the technical, cultural, ecological, social, architectural and economic dimensions [73]. A review of tools for refurbishment decision support showed that 81% contained environmental criteria, whereas only 63% contained social criteria, often in relation to indoor climate [74]. Since building refurbishment also has the potential to contribute to major social improvements, it is important that the environment and economy are not the only focus point in decision-making processes for choosing the best refurbishment strategy [75]. An example of how refurbishment decision support can be used practically in an urban context is Copenhagen Municipality's financial support for building renovations. Here, in addition to a focus on achieving energy savings, there is also a strong focus on the social criteria for improving the indoor climate and thermal comfort. There is also a focus on improving installation deficiencies such as a toilet and bath in the home, which is relevant for the 2,900 homes that lack their own toilet and the 17,600 homes without a bath in the Copenhagen Municipality [76].

Over the past few years, research into refurbishment has evolved from being technology-focused to being management-focused [77]. However, the choice of individual technological solutions has a particularly large impact on the potential environmental, economic and social savings. One of the major barriers to major renovation projects is often financial, which may be rooted in the fact that extensive renovations of technical structural systems or energy optimization to low-energy classes can be expensive and time-consuming [78]. Implementation of more pre-fabricated technical solutions in building refurbishment can reduce the construction time in the refurbishment process [79]. Prefabricated solutions can, however, mean that more components must be removed from the existing building and subsequently more new materials added. This can increase both the material consumption and the environmental impact when using prefabricated solutions in refurbishment [80]. However, there is a tendency in Denmark for apartment buildings to have a larger part of the building elements removed and replaced, instead of their being maintained during the renovation, such as the windows, roof coverings or facades [81]. Here prefabricated solutions are a possibility.

1.3.3. Adaptive reuse of existing buildings

The research interest in adaptive reuse has increased within the last few years, which means that sixty articles were published in scientific journals in 2020 dealing with adaptive reuse, against fourteen articles in 2018 [82]. The term ‘transformation’ covers a fundamental change to the building which either resulted in or was forced by changes in behaviour or needs [83]. Because adaptive reuse is derived from a changing demand for the building's functions, the term ‘transformation’ is often used in relation to or instead of ‘adaptive reuse’. From an architect’s point of view the objective of adaptive reuse is often to avoid the demolition of old heritage buildings and thereby save historical and cultural value [84]. Adaptive reuse is typically applied to historic industrial buildings, for example, in Poland, where a large number of old power-plant buildings have been transformed into galleries and museums [85].

By applying adaptive reuse, the need for new materials is reduced because adaptive reuse requires fewer materials than new construction [86]. This is partly because a large amount of the existing materials, such as the load-bearing system, is often preserved. Adaptive reuse can therefore help to drastically reduce the environmental impacts of construction because around 70-75% of the CO_2 emissions from materials come from the heavy structural elements [87]. Against this background, environmental savings of between 20% and 41% can be achieved in relation to the total environmental impact of new construction in six out of seven impact categories if the supporting system is preserved, even if the majority of the remaining building elements are replaced [88]. Adaptive reuse projects are often more complicated than refurbishment projects, but they also contain opportunities to contribute more value and functions to the surrounding community that are often overlooked [89,90]. Tools and calculation methods for the holistic evaluation and identification of the adaptive reuse potential are therefore important in order to realize the full potential of adaptive reuse [91].

Various studies have tested multi-criteria decision-aiding (MCDA) methods in order to rank adaptive reuse strategies via the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) [92] or by combining the Analytic Hierarchy Process (AHP) with Discounted Cash Flow Analysis (DCFA) to assess the financial feasibility [93] of the adaptive reuse of old industrial heritage buildings in Italy. More qualitative methods have also been developed for assessing adaptive reuse strategies that, through a large number of case studies, have identified issues and building factors that affect whether a building is suitable for adaptive reuse [94]. However, it can often be difficult to collect the necessary data. Therefore BIM (building information modelling) models, combined with 3D scanners and non-destructive test methods, can be an advantage in the planning of necessary deconstruction processes prior to an adaptive reuse project [48].

Buildings that are transformed through adaptive reuse often contain technical properties such as a surplus of space, additional loadbearing capacity (often based on columns) and easily adaptable or removable facades, which means that the buildings often result in transformed buildings with a lifespan that is much longer than the expected standard lifespan for new buildings [95]. The long-term perspective for transformations from industry to housing can also be a challenge because office investors have a shorter investment horizon and are therefore only willing to invest in the housing market to a limited extent [96]. In order to make adaptive reuse financially profitable, it is therefore important that housing associations acquire buildings in areas where demand for offices is low so that the office building can be acquired at a low price prior to its transformation into housing [96].

1.4. Circular Construction in Regenerative Cities (CIRCuIT)

This PhD project is mainly funded by the EU Horizon project CIRCuIT (Circular Construction in Regenerative Cities). It is therefore also the CIRCuIT project that has helped to define the scope of the PhD project and how it has developed. CIRCuIT consists of 32 partners distributed between London, Helsinki, Hamburg and Copenhagen, which include local authorities, architects, demolishers, contractors, housing companies and universities. The project was launched in 2019 with a grant of 9.8

million euros from the EU Horizon 2020 program and is scheduled to be completed in November 2023. The main project is divided into 9 WPs (work packages) (see Figure 3), where there is initial data-mapping (WP3), a main part dealing with strategies and methods for urban mining (WP4), transformation (WP5) and flexibility (WP6) in construction, as well as a final dissemination and governance part (WPs 7-9). The purpose of CIRCuIT is to bring together theory, practice and policy by investigating and demonstrating circular construction approaches in the four cities and creating a showcase for how similar approaches can be used in other cities to promote circular construction at the policy level. In addition, the goal is also to provide a material stock and flow database that can be used to exchange circular materials and at the same time develop circularity indicators that can be used to monitor circular construction on a city scale.

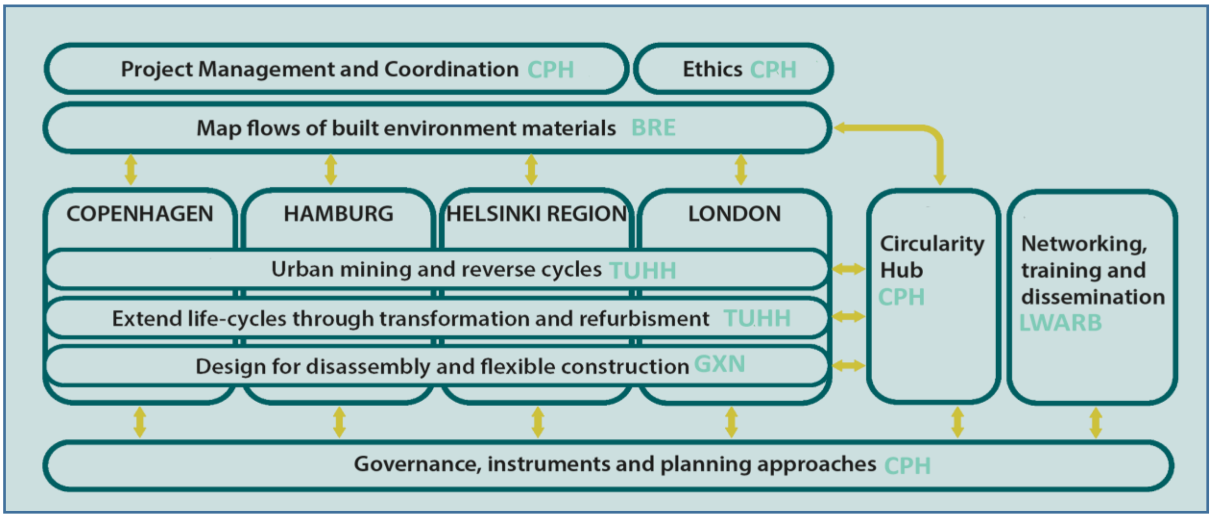

Figure 3. Framework for CIRCuIT.

DTU has been responsible for the data part in Copenhagen regarding data on existing buildings and material flows in construction. This has led to the publication of three CIRCuIT reports on the state of the art in respect of material flow data [97], recommendations for improving the capture of material flow data [98] and recommendations for circularity indicators [99], to which the author of this PhD thesis contributed with mappings of building data in Denmark, facilitated workshops for stakeholders from the construction industry, and contributed text and editing to the reports. In addition, most of the authors' work in relation to CIRCuIT has been performed around life-cycle extensions, transformations and refurbishments, on which a report has so far been published for which the author wrote a chapter describing how to identify buildings for life-cycle extensions [100]. Knowledge of the work performed in connection with CIRCuIT and from the preparation of the reports will therefore also be included in the three main parts of this thesis.

2. Knowledge gaps and barriers in circular construction

Based on the literature review described in the previous chapter, the following data gaps were identified in relation to circular construction:

1. **Data for existing buildings.** Data is a fundamental foundation for performing assessments on buildings. However, input data for calculations or simulations can be both time-consuming and expensive to collect, especially if the analysis covers several buildings or when performing screenings of the built environment at the neighborhood or city level. Several government strategies also focus on the digitization of construction and the use of big data. There is therefore a need to investigate what the data availability is for existing buildings, how to establish and organize registers, to what extent the currently available building data can support assessments in circular construction, and what is the quality of the existing data.

2. **Demolition trends and patterns.** Many sustainability initiatives focus on new construction, but there is generally a lack of knowledge about our existing buildings. Some studies are beginning to assess the environmental impacts of renovation strategies, concluding that in most cases there are environmental and resource advantages in renovating or transforming rather than demolishing and building new. At present, there is no knowledge in Denmark about the dynamics of demolition and why some buildings are demolished while others are preserved. At the same time, the building lifespans on which we base our LCA and LCC analyzes are focused on new construction and therefore may not be accurate for the demolition of existing buildings.

3. **Materials and components.** Construction is one of the largest generators of waste, but today much of the waste is deposited or recycled at low-value (down-cycled), typically as backfilling or as base layer in road construction or on construction sites. As described in knowledge gap 1, there is generally a lack of knowledge about data in existing buildings, and this also applies to the materials and the component composition of existing buildings, as well as their circular potential for reuse or high-value recycling. At the same time, circular demolitions differ from the more conventional demolitions as they are often more selective and require more manual work and time, so there is also a need to expand our knowledge of the environmental impact of materials- and component-handling from circular demolition processes.

4. **Adaptive reuse, transformation and flexibility.** The sustainability focus in the construction industry and in research is mainly on new construction, but there is starting to be more of a focus on renovation. Adaptive reuse, transformation and flexibility, on the other hand, is less present in either actual performed construction projects or research. Since adaptive reuse projects are often more complicated than refurbishment projects, this also makes the pre-

assessment that must be carried out on existing buildings to investigate whether they are suitable for transformation more complicated. A few tools already exist to measure flexibility for adaptive reuse, but there is a lack of knowledge about how flexibility can be measured and how the best transformation strategy can be selected for existing building typologies.

3. Research methodology

A circular economy should ideally be not the end goal but a tool that is used to achieve more sustainability. Since circular construction and sustainability are very closely linked, the scientific method in this PhD project is based on the principles of sustainability science [101] . The core of the PhD thesis is a collection of six scientific articles (see Table 1) that have been published throughout the three-year PhD project. The abbreviation "*JP"* stands for Journal paper, *"CP"* stands for Conference paper. Each article addresses research questions related to circular construction where different methods within sustainability science have been used. The *analytical-descriptive* method was used to investigate and understand the background trends within demolition (CP2) and the lifespans of existing buildings (JP4), whereas the *solution-oriented* method was used for renovation indicators and data-mapping (JP1), transformation tools (CP1), material predictions (JP2) and LCA studies (JP3). These methods were deployed through literature studies, data-mapping, case studies, LCA calculations and statistical analyses, as well as the designing and testing of various simulation and calculation models in order to inform the architectural design process.

Table 1. Articles published in relation to this thesis report and their relevance to the three main parts of the report.

Abbreviation*	**Title**	**Journal / conference**	**Knowledge gap(s)**	**Connected to**
JP1	Using digitized public accessible building data to assess the renovation potential of existing building stock in a sustainable urban perspective. (Published December 2021)	*Sustainable Cities and Society*	1+3	Part 1
JP2	Parametric Stock Flow Modelling of Historical Building Typologies. (Published September 2022)	*Buildings*	1+3	Part 1
CP1	Multi-criteria analysis of buildings transformation potential in planning and design. (Published July 2022)	*ISCA 2022 Aalborg*	4	Part 3
JP3	Environmental benefits of applying selective demolition to buildings: A case study of the reuse of façade steel cladding. (Published September 2022)	*Resources, Conservation & Recycling*	2+3+4	Part 2+3

CP2	Adaptation of circular design strategies based on historical trends and demolition patterns. (Published October 2022) *(This article was awarded the Outstanding Paper Award at SBE22 Delft)*	*SBE 2022 Delft*	2+4	Part 2+3
JP4	Lifespan prediction of existing building typologies. (Published April 2023)	*Building Engineering*	2	Part 2

Circular construction is a very broad term, so in order to improve the overview of the subject, the report is divided into three main parts (see Figure 4), each of which deals with a theme in relation to circular construction. The first part focuses on expanding and mapping our knowledge of the existing building stock through data-mapping, legislation and the testing of data quality for materials in existing buildings. The purpose of implementing circular strategies in construction is to avoid or reduce construction waste. Therefore the focus in the second main part of the report is on expanding our knowledge of trends in demolition and the lifespan of buildings through an extensive collection of data on demolitions. The last part of the report will quantify the potentials of implementing circular design principles for existing buildings.

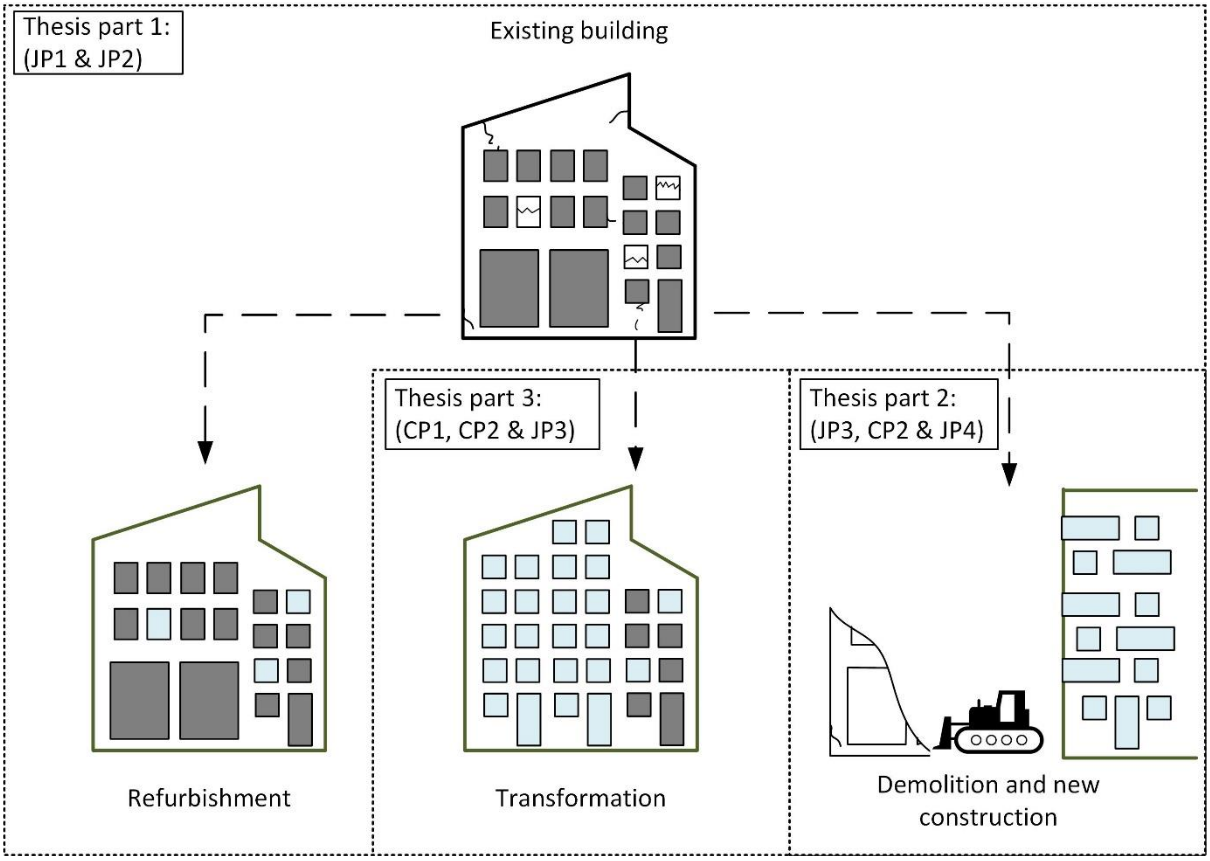

Figure 4. Building adaptation strategies for existing buildings and their coverage in this thesis report.

4. Part 1: Mapping of available data on the existing built environment and material stocks in cities

The construction industry is experiencing a major digital transformation, which means that construction has become very data-intensive. Although the construction industry creates large amounts of data, it has not managed to exploit opportunities within Big Data technologies to the same extent as other sectors [102]. Information systems in construction are often isolated from each other, meaning that data may be inaccurate and inconsistent, while at the same time there can be problems in relation to the traceability and reusability of data in construction companies [103].

This chapter will present the study on data in the existing building stock, with a focus on investigating the extent to which it is possible to quantify circular construction today. Methods such as data-mapping will be used to determine what data is currently available on buildings in Danish registers and how these registers are established and structured. In addition, our knowledge of materials in the existing building stock will also be tested, and a model will be sketched for how the quality of data on materials in existing buildings can be improved. Finally, the future potential of data in construction will be assessed and discussed.

4.1. Mapping of data availability on existing buildings through registration requirements

There are generally seven main laws that regulate construction in Denmark (see Figure 5). They have been drawn up on the basis of regulations regarding historic buildings and value, taxation, energy, the environment and construction techniques. In addition, the so-called Planning Act helps to determine the framework within which municipalities can process construction cases and determine the requirements for new buildings, as well as a legislation that is focused on geolocations and maps. Each of the main pieces of legislation has its own specifications and guidelines, which also help to regulate construction on the basis of the main pieces of legislation. In order to identify where data on buildings is generated, Danish building legislation was reviewed in order to investigate where and how registration requirements were established and whether there were any specific requirements for how this data must be collected and stored.

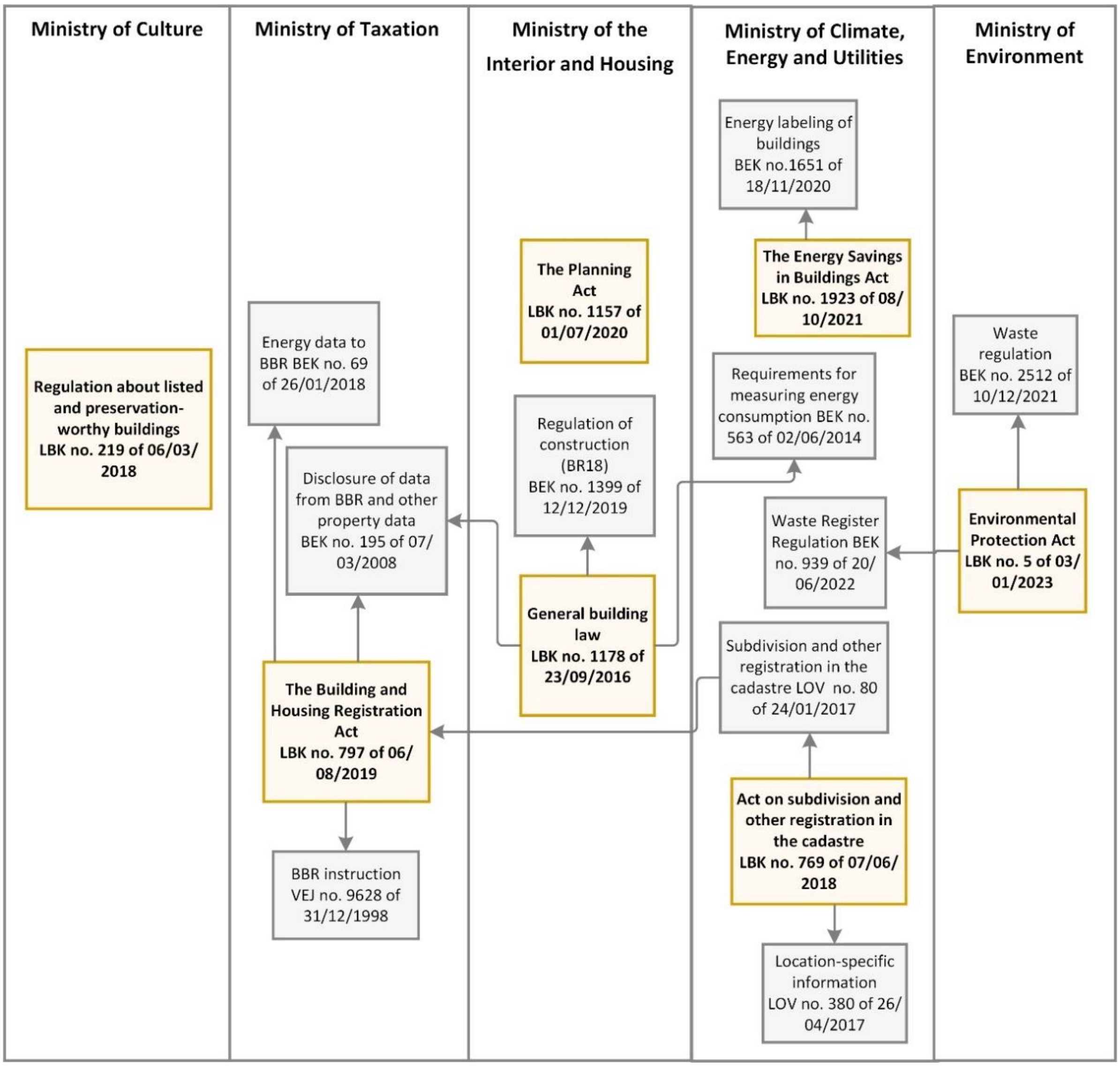

Figure 5. Structure of Danish legislation covering existing buildings and new construction (edited and updated from [104]*).*

The initial review of building legislation was carried out in spring 2020 in connection with the CIRCuIT project, where the author of this thesis carried out a mapping of data availability in Denmark. A review of the available data was then carried out in each CIRCuIT city with a focus on identifying data that could be used to generate and inform circularity indicators. Afterwards, the cities' data availability and registration structures were compared and published in a CIRCuIT report [97]. The main conclusion was that Denmark is one of the CIRCuIT countries with the most publicly available data on existing buildings, followed by Finland. The comparison also showed that there are many similarities between how Denmark and Finland collect and store data and that there were very large similarities between the two countries' main building registers, which are largely identical. Subsequently, it has also been shown that Sweden uses a building register which is very similar [105]. This therefore makes it much easier to perform similar analyses in the Nordic countries based on data from building registers. The analysis also showed that London and Hamburg had large data gaps for existing construction and that there was generally no overarching national standardized building register so that the availability of data depended greatly on the efforts carried out by the individual cities. There were therefore great opportunities for Hamburg and London to gain experience from Finland and Denmark in creating a national framework for publicly available data. Four public and one semi-public databases were identified in Denmark, which have also formed much of the data base for the analyses carried out in this PhD project.

4.2. Publicly available data

4.2.1. The Danish Building and Dwelling Register (BBR)

The BBR (Bygnings- og Boligregistret) is Denmark's central building register, which contains data on all buildings and is legally defined in LBK. No. 797 from 2019 [106]. The BBR was officially established in 1976 [105], but the registration of housing conditions started as long ago as 1880, when the Municipality of Copenhagen began to collect information on housing, which was then distributed to all municipalities in 1955 [107]. The data in the BBR are registered at three levels, namely the cadastral, building and unit levels. The registrations cover many building-relevant parameters, such as areas, uses, types of energy and heating, floors, access conditions, years of construction and/or renovation, roof and wall materials, number of rooms and their functions, and various building functions such as the number of bathrooms, toilets and kitchens. There are a total of 36 registration conditions at cadastral level, 68 registration conditions at building level, and 34 registration conditions at unit level. The majority of these registration conditions are publicly available via various online portals, but some registration conditions are only available to the building owner (e.g. measured energy consumption). It is the building owner's responsibility to ensure that building data in the BBR is correct.

4.2.2. Register for Listed and Conservation-worthy buildings (FBB)

The FBB (Fredede og Bevaringsverdige Bygninger) register contains data on listed and conservation-worthy buildings [108]. The conservation value is calculated on the basis of the SAVE method (Survey of Architectural Values in the Environment), where an expert committee physically inspected buildings and ranked them on a scale from 1 to 9, where 1 is the best score and indicates a high conservation value. This is normally referred to as the SAVE value, which is calculated based on the overall score for five indicators: architectural value, cultural-historical value, value for urban identity, originality and the condition of the building. Both the SAVE value and the assessment of the five underlying indicators are publicly available in the FBB register. In addition, there may also be an in-depth description of important architectural elements on the assessed building. However, only a small portion of the total building stock has been SAVE-evaluated, which means that SAVE data is only available for 370,000 buildings [109] out of the total Danish building stock of 4,474,174 buildings [110]. In addition, SAVE has only been updated to a small extent since the 1990s, when most assessments were carried out, so most of the assessments are around thirty years old and are therefore no longer accurate because of later changes that may have been made to the building. At the same time, buildings constructed after the

1960s are only evaluated by SAVE to a small extent because they were assessed as newer buildings when the FBB register and SAVE were established in the 1990s. Today, however, these 1960's buildings form a large part of the existing building stock, having reached an age where they require renovation and are often at risk of demolition.

4.2.3. Energy label data

According to the Energy Savings in Buildings Act LBK no. 1923 of 08/10/2021 [111], the Minister for Climate, Energy and Supply is responsible for creating a register containing all energy labels in Denmark, as well as the technical information for building parts and technical installations that are registered in connection with the preparation of the energy label. It is possible to access energy labels online in pdf format, which contain a description of the building parts and the calculated energy label. In addition, the owner of a building has full access to all the registered background information and calculations used to calculate the energy label. This registered information includes stated energy consumption, floor and building parts' areas and the insulation properties of building parts, as well as technical specifications for the ventilation and heating systems in the building. It is mandatory by law to have a valid energy label when selling or renting a building or apartment. For new buildings, the energy label is used to check whether the building complies with the requirements for new buildings. In addition, all public buildings over 250 m^2 must always have a valid energy label. An energy label has a validity period of ten years, making it possible to sell a building several times over on the basis of the same energy label if this is within the validity period of ten years.

4.2.4. Construction case archives

Most municipalities offer digital access to building records for historical drawings and earlier applications for construction work. This is an invaluable tool for obtaining knowledge about historical changes made to a building through the case files or old drawing material. The files in the construction case archives are usually scanned documents in pdf format. There are many differences in how much historical building data is available for individual buildings, and some types of building files are not publicly available. There is no requirement to establish a central building case register, but there are currently two main registers at filarkiv.dk and weblager.dk which most municipality's use, while some individual municipalities have created their own solutions. Some cases of construction are also registered in the BBR, where all cases of construction regarding demolition, new construction, extension, conversion and renovation are processed.

4.3. Semi-public or private data

4.3.1. Construction waste reported to municipalities

According to the Waste Order BEK no. 2512 of 10/12/2021 [112], screening for hazardous substances such as asbestos, PCBs (polychlorinated biphenyl), heavy metals and PAHs must be carried out before the start of demolitions, renovations and maintenance work, as well as when replacing double-glazed windows produced between 1950 and 1977. The screening must be submitted to the municipality no later than two weeks before the start of the demolition via a digital self-service platform that the municipality must make available for reporting. Along with the screening for harmful substances, is it also mandatory to report what types of waste are generated, the individual quantities of waste fractions in tonnes, and the expected handling of the waste (reuse, recycling, incineration or disposal). When the notification is approved by the municipality, the case is assigned a unique ID number. When the waste is subsequently removed from the building, the unique ID number must be provided when the waste is handed over for handling or sorting, so that the actual weighed quantities are subsequently registered on the original case file registered with the municipality. There is no national database for construction waste, and it is therefore up to individual municipalities in Denmark to make a digital reporting portal available either by developing one themselves or by buying the service from a company, which is the more typical choice for municipalities. Although it is possible to obtain construction waste data by contacting the relevant municipality, since it is the individual municipalities that own the data, it is not possible to make large extracts of data for the whole of Denmark, as is the case with the BBR, FBB register and energy label register. If data is obtained for the whole of Denmark, it will be in a different format, while permission must be obtained and data-processing agreements made with all 98 of Denmark's municipalities.

4.3.2. Companies' own data from construction processes, facility management etc.

The last category of data on buildings is all the data owned by companies that operate within the construction sector. This can be anything from maintenance plans, drawing materials, calculations, BIM models, measurement data and construction management tools. This data is usually not publicly available, but it can potentially contain a very large basis for creating more knowledge about both new and existing buildings, as well as more knowledge of construction processes. It is typically this type of data that will be used in connection with research collaborations with companies.

4.4. Material data on Danish building typologies

As described in Knowledge Gap 3, there is generally a lack of knowledge about what materials our buildings consist of, both existing and newly built. The reason why the material composition of buildings is important for circular design is that it is the current materials embedded in existing buildings that will become the circular materials of the future. At the same time, knowledge of how much waste is generated in connection with renovation and demolition and the possibilities for these materials to be included in circular flows is also important in being able to assess the most environmentally friendly design options in planning the construction. Because there is currently very little knowledge about materials and components in existing buildings, this section will investigate how more knowledge can be created about materials in buildings based on the registered construction waste data described in section 4.3.

4.4.1. Static material flow analysis for the assessment of existing building materials

There are different methods for calculating or estimating materials in the existing building stock. Some of the most frequently used methods in construction are static material flow analysis, which provides a snapshot of which materials are included in the entire building stock or in a specific building type, and dynamic material flow analysis, which considers changes in material flows over time, e.g. changes in the input and output of materials. Common to all types of material flow analyses is the fact that they requires some basic data about either the consumption of new materials, case studies of materials in certain types of existing buildings, or the registration of waste data in order to be able to make a bottom-up or top-down assessment at the building-stock level.

The building stock is extremely complex and consists of buildings from different construction periods with different uses. The most frequently used method in relation to material flow analysis within buildings is therefore to subdivide the stock into building typologies on the basis of similar characteristics for the construction period, the building's use or based on the type of the structural system and thereby only consider a section of the building stock based on the chosen typology. Similar methods using building typologies are also used in analyses of energy consumption, where one of the most comprehensive typology studies is the TABULA (Typology Approach for Building Stock Energy Assessment) project [113], where European buildings are divided into typologies on the basis of their year of construction and energy characteristics. In relation to the assessment of materials and components, it may be relevant to divide buildings according to construction periods where there has been a change in building practices and thus a change in the materials and components that were used for new buildings in that construction period, as well as the building's use, which is also included to define which materials were used. In Denmark, the BBR register is a good starting point for dividing existing buildings into typologies, since the register contains data on the year of construction, the building use and the primary materials used in the outer walls and roof.

In order to be able to make accurate material flow analyses, there should preferably be a large data source about materials available, such as register data. Since most countries do not have building-level registrations of materials (or material passports), or large typology studies of the materials composition of existing buildings, material flow analyses are often based on a few case studies of demolished buildings or pre-demolition audits of existing buildings. Due to limited case studies, it can be difficult to scale up the building stock level because, even within the different typologies, there can be great variation in the materials used, the layout, the replacements and the condition of the building parts. By using register data, it is in principle possible to divide the building stock into as many typologies as there are data points, allowing a much more complex targeted analysis to be made for all historic typologies. In Denmark, the BBR covers all buildings and can therefore be used to create typologies and to scale up material data for all demolished buildings registered with the municipalities that were identified in section 4.3.1. A static material flow analysis based on a linear regression model was therefore tested based on the data set for construction waste reported to the municipalities to see if it would be possible to determine the material composition of Danish building typologies. However, it turned out not to be possible to make precise material predictions for three reasons: i) problems accessing data, ii) registration structure, and iii) the quality of the reported data.

1. The first challenge is the limited access to waste data from demolitions, which is partly because the data is not structured in one common database. Instead, the data is scattered in many different databases in different formats. Also, because the data is not publicly available and is owned by each individual municipality, it was not possible to make a single extract for all Danish municipalities due to the GDPR (General Data Protection Regulation). Moreover, with 98 municipalities in Denmark, it can be very time consuming to establish data-processing agreements with all of them. It was therefore only possible to obtain data from the Municipality of Copenhagen, based on an existing GDPR data-processing agreement.

2. At present, there is no data connection between the BBR and the registration of construction waste, as there is, for example, between the other public databases. It can therefore be very difficult to link the registered construction waste to a specific typology because the reports are made at the address level without the building's ID. The extraction of waste data is focused on making reports and handling demolition cases in the municipalities and not on statistics, so it requires a lot of post-processing of data to create a dataset in a format that is suitable for making statistics, where, for example, one demolition case with all the associated information is listed in the same row. At present, data for one case of demolition is spread over several rows and columns in the same data extract. Furthermore, it is also difficult to analyse the reuse potential at the component level because all registration only takes place at the material level.

3. One of the biggest limitations in making correct analyses of material flows based on the construction waste data is the quality of the data. Our test [114] of the data quality showed that there were many input errors in the data where incorrect values were entered in various fields. For example, instead of inserting the correct floor area of the building the municipality number was entered, while a telephone number or the year of construction might be entered by mistake in the floor-area box. The material quantities should be registered in whole tonnes, but there were also examples of errors where materials were being reported in kilograms instead of tonnes, which gives a factor of 1000 in the error rate. There were also many examples of buildings being reported multiple times or demolition cases reported at the wrong address. During a subsequent interview with a municipal employee who is responsible for handling the reported demolition cases, it became clear that the municipality discovered most of the errors

in their internal processing of demolition cases, but because the data is not used for statistics, only a note was written when errors where identified. The errors were not subsequently corrected in the database, which is the main reason for the many errors in the extraction of construction waste data.

3.1.1. Parametric modelling for assessing materials and components

Information about building parts is important in assessing the reuse potential of components at the building level. A knowledge of building parts is also fundamental for the ability to assess the potential for improving the existing building through refurbishment or transformation. This is not currently possible based on the construction waste data since it is only listed at the material level. It is therefore necessary to create an overview of which building components are used in different building typologies in Denmark, and how. An in-depth typological study can be very time-consuming because it will be based on physical audits in order to measure and register building parts and construction techniques in many different types of building. Fortunately, extensive typological studies of multi-storey buildings in Denmark have already been conducted by [115,116] which describe construction techniques and variations in building parts for the different construction periods of multi-storey buildings. This data can therefore be used to obtain an overview of which building components can be found in different typologies. By using parametric modelling in Grasshopper, a geometric model based on predefined typology structures can be set up. Moreover, using Boolean rule-based modelling, data from the BBR can be used to identify and specify the typology (see steps 1-3 in Figure 6), so that the parametric model can assess the most likely construction technique to have been used and thereby generate a 3D model of the building with the most probable component structure. It is especially the 3D aspect that is the advantage of the parametric modelling because that makes it possible to validate the generated model against a visual inspection (see step 12 in Figure 6) of the real existing building and thereby improve the quality of the prediction of building component and materials.

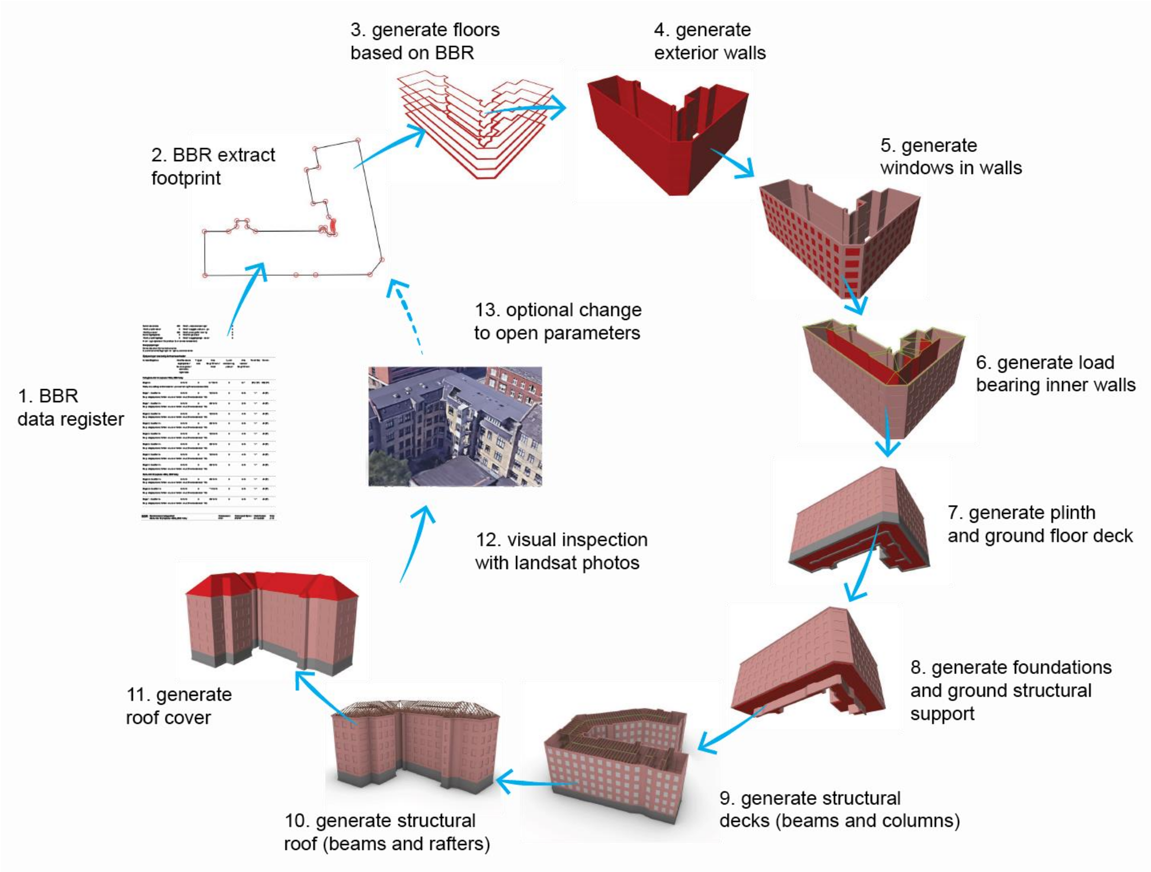

Figure 6. Auto-generation of a building model with structural constructions in eleven steps on the basis of BBR data and typology studies followed by two steps of model inspection and revision [114].

Because the parametric model contains specific building components and is easier to validate, it is better for predicting both the component and material compositions of buildings, and for assessing future opportunities for reuse by making a 3D building model. More typological studies of other building uses, such as single-family houses, offices and industrial buildings, are therefore needed before parametric modelling of the building stock can become operational and support the quantification of circular materials in existing buildings in the wider building stock.

3.2. How to improve data quality and the capture of material and component data on buildings

Although there is a lot of data on buildings in Denmark, data on materials is still lacking, and the quality of the existing data is generally poor. One of the reasons for the poor material data is partly the lack of focus on correcting mistakes in data and the fact that construction waste data has historically been based on a guess of assessed quantities before the demolition (pre-demolition audit) and not the actual measured quantities after the demolition. However, this has been changed in the new waste legislation [112], in which the pre-demolition audit must be registered, as must the actual weighed quantities when they are handed over to a waste-treatment facility. In principle, this makes it possible to obtain much more precise data on the actual quantities that are generated from a specific demolition and at the same time improve pre-demolition audits because the errors between the estimated and actual quantities of construction waste can be quantified. The new waste requirements have only been operational for less than a year, and therefore it has not been possible to make a new calculation based on the new requirements, especially because in many cases the actual quantities prescribed by the legislation are not reported. At present, there is no penalty for not reporting actual waste quantities, and there are also various reporting problems surrounding the mixing of several waste fractions and the separation of materials from several projects that have been transported to the same treatment facility. It may therefore take several years before the necessary high-quality data on materials is available on a larger scale. There is also still a lack of a connection between the reported demolition cases and the BBR in order to be able to divide the reported waste into typologies based on the BBR's classifications.

In general, linking data from different databases is a good method of validating data and identifying inaccurate registrations, thereby improving quality [117]. Examples of the benefits from this method can be seen in how, by using data from satellites and geodetic registers, it has been possible to identify buildings in the BBR that need to be registered and buildings where there are large deviations in area. There are already connections between the FBB register and the BBR enabling the exchange of information about the existing buildings and the connections between the energy labels and the BBR to validate the areas and registration of energy installations. This can also be used to create larger data sets when most of it is connected to the BBR. This makes it possible to establish some combined data sets with large amounts of data about existing buildings that are more easily implemented in GIS maps to create building stock assessments or combine all the information in building data passports.

There can be future potentials in relation to artificial intelligence (AI), which can solve complex problems to a greater extent by coming up with accurate analytical results on the basis of the uncertain and intensive data that is often found in construction [118]. AI can be used to make analyses of the existing building stock and the dynamics that influence whether a building is demolished or not and at the same time improve some of the problems with the poor quality of data on building materials over time. This is an advantage because over time AI should become better at predicting the material composition of a building if the entered data is validated with inspections and measurements. In construction, large amounts of visual data, such as images and videos, are also created as part of the construction process. Because a lot of visual data is often not handled correctly and, for example, is stored in BIM models, it often quickly becomes unusable [119]. However, these images can be used to a greater extent to document the condition of a building and identify building parts via image recognition. BIM models also contain good opportunities to create better handling and storage of data, but at present BIM technology is mainly used in the design and pre-construction phases [120]. Currently, there is no common publicly available database for BIM models in Denmark. A greater focus on making BIM models available will therefore improve the opportunities to access and store additional data in the models which can later be used to assess their circular potential.

5. Part 2: Trends in the demolition and life-cycles of buildings

It is often said that the most sustainable buildings are those that we do not build, but simply preserve through either refurbishment or adaptive reuse. The vast majority of existing buildings are preserved, but every year a large number of buildings are still demolished in Denmark. There are several studies that have tried to investigate the reasons for such demolitions. Some point to a change in needs in relation to functions or economic considerations for the building as reasons why buildings are demolished [121]. Other studies indicate that it is most often social or economic parameters in relation to the location or surrounding area of the building that influence whether or not it is demolished [122,123]. No matter what the reasons are for buildings being demolished, demolished buildings are an important resource in relation to circularity. If the demolition can be avoided through either refurbishment or adaptive reuse, the need for new construction will decrease, while if the demolition cannot be avoided, is it important to get the most out of the materials through reuse and recycling. However, knowledge about demolition patterns and future potentials is lacking. At present, there is very little knowledge about the dynamics of the demolition of existing buildings in Denmark, and while statistics are collected annually on new construction and the existing building stock, there are no statistics in Denmark on which buildings are demolished or how many. Therefore, there is an urgent need to create more knowledge on demolitions in order to be able to assess how much of our need for new construction and materials can be covered by either avoiding demolition or maximizing the utilization of waste materials from demolitions.

This chapter will analyse trends in demolition in Denmark through extensive data collection on the basis of the data identified in Part 1. By means of statistical analyses, the collected data will provide answers regarding which buildings have been demolished in Denmark historically. It will also help identify which buildings will be demolished in the future through a better knowledge of the lifespan of buildings and how we can obtain the most climate benefit from buildings that are demolished by using circular demolition strategies.

5.1. Collection and processing of data on historic demolitions

Data from the BBR was used in order to create a dataset of demolitions in Denmark [124]. When a building is demolished, the following dates are registered in the BBR: i) date when the building owner applied for approval from the municipality to demolish the building; ii) date when the municipality approved the demolition; and iii) date when the building has been notified to the municipality as having been demolished. The building is then deleted from the BBR and is therefore no longer visible in the BBR register. It is therefore not possible to access information about demolitions through the normal online BBR portals that are used to retrieve the data for the existing buildings. Large-scale BBR data are normally received via the online service Datafordeler.dk, an online platform that provides access to basic data from public authorities in Denmark, but because cases of demolition are deleted after the demolition, was it not possible to extract any data. The technical part of the BBR register is administered by the Danish company KMD. Together with the municipality of Copenhagen, it was possible to extract annual lists from the BBR which contained all the buildings in Denmark that had been registered in the BBR as having been demolished in the year in question. It was then possible for KMD to make an extract of the BBR's information for buildings at the beginning of the year. This information, from the first day of the year, was then linked to the buildings that had been registered as having been demolished during the year. This created an annual dataset from BBR-associated data for all demolished buildings. This was then repeated for each year from 2000 to 2020. This resulted in a dataset of 152,288 cases of demolition between 2000 and 2020. However, around 28,204 of the cases did not contain the necessary information to make a correct dating and were therefore removed, leaving the final dataset with 124,084 cases of demolition. Very few cases were registered before 2010 (See Figure 7), which may be due to restructuring of the BBR reducing the focus on the registration of demolitions. There are also significantly fewer cases of demolition in 2020, since the data set was extracted in the spring of 2020 and therefore does not cover the whole of 2020.

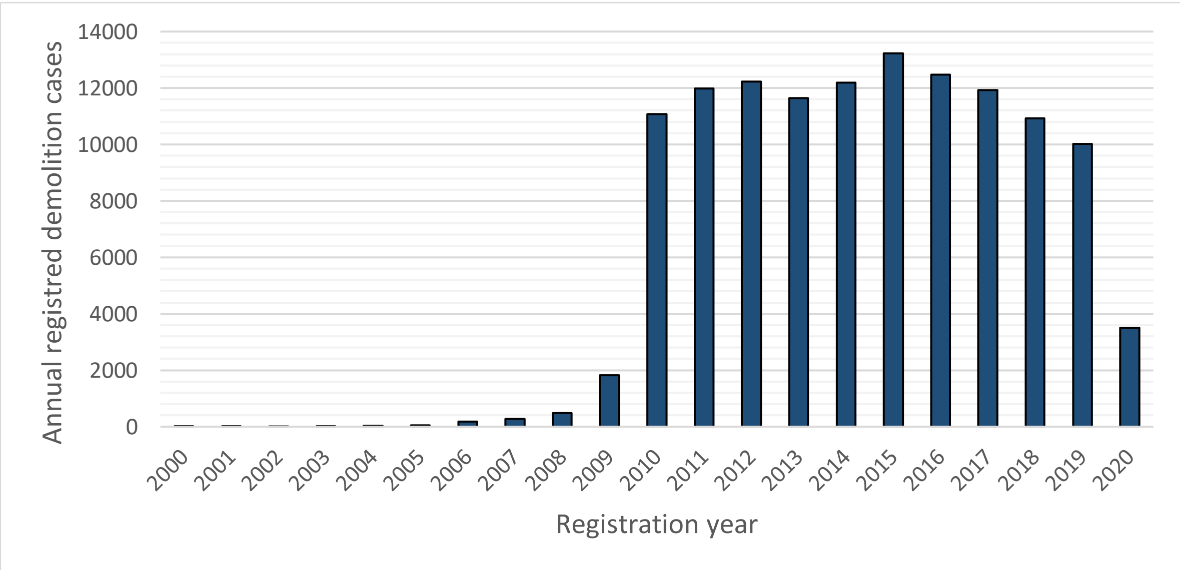

Figure 7. The distribution of the annual number of cases of demolition extracted from the BBR.

Each demolition file contains a municipality identification code, the year(s) of construction and renovation, the code of use, exterior wall and roof materials, floor areas, heating installation and ownership. Changes have been made to the BBR over time where, most recently, the use codes that describe the use of the buildings have been increased from 28 use codes to 87 use codes. The new use-code system contains many more subdivisions, but because the buildings are still being updated, there are some buildings with the old codes. Much of the historical data is also recorded on the basis of the old use code-system, and therefore in the following statements the old system of 28 application codes has been used. In order to simplify the calculations, they have been reduced further to 13 different types of use, so that housing now covers 7 different types of housing. Finally, demolitions from before 2010 and from after 2019 were removed in order to create a uniform dataset that ended up with 117,694 cases of demolition carried out from 2010 to 2019 inclusively. Data on existing buildings are based on data from Statistical Denmark's data set BYGB34, an annual overview of the floor areas of the existing building stock divided by municipalities, types of building use and construction periods.

5.2. Historical demolition patterns and expected future trends

The average annual demolished floor area from 2010 to 2019 is equivalent to 0.26% of the existing floor area of the building stock. Housing is the building use that has the lowest demolition rate at around 0.11%, whereas manufacturing buildings (0.4-0.57%) and childcare buildings (0.52%) have the highest demolition rates. By comparing the distribution of the demolition with the distribution of the existing building stock in Denmark (see Figure 8) and Greater Copenhagen (see Figure 9), it is clear to see that there are relatively large differences between how the demolition is distributed locally and nationally. Both in Greater Copenhagen and nationally 20% of the demolished square meters had been used for housing (typically single family houses), but nationally housing makes up 45% of the existing building stock, whereas in Copenhagen it makes up over 60% of the existing floor area of the building stock. In terms of housing, Copenhagen therefore rates lower than the national figure. It is therefore clear that the tendency to demolish housing is greater nationally than it is in Copenhagen. Some of the difference can be explained by the fact that many square meters of agricultural buildings are demolished nationally including housing in relation to agriculture, a building typology that is not present in Copenhagen. Nationally, agricultural buildings make up a third of all demolished square meters and are therefore the building type most subject to demolition. In Copenhagen, it is typically industrial buildings that account for the vast majority (over 50%) of demolitions, with offices and warehouses in particular making up a very large proportion. This is despite the fact that these building types only make up about 20% of the existing building stock. It is therefore clear that demolition is not distributed equally between either areas or building types in relation to how much they make up of the existing building stock.

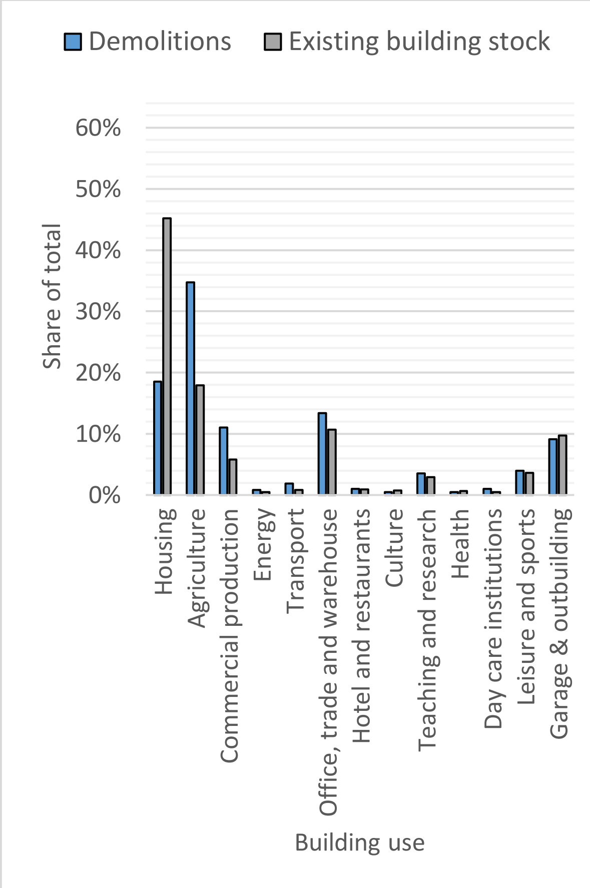

Figure 8. Demolition share from 2010-2019 in Denmark for different building uses compared to the share of existing buildings from 2010-2019.

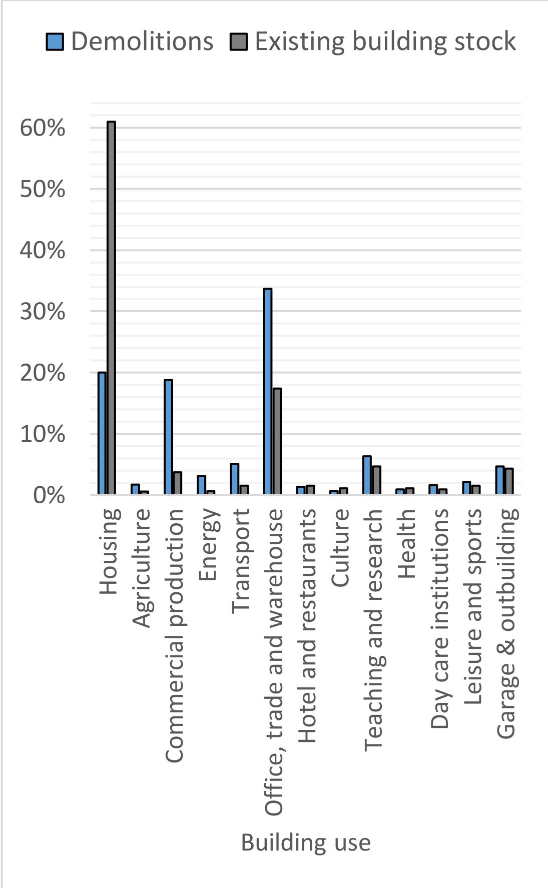

Figure 9. Demolition share from 2010-2019 in Greater Copenhagen for different building uses compared to the share of existing buildings from 2010-2019.

When the demolitions are grouped by year of construction for the demolished building, it is clear that in Denmark (See Figure 10) there is a relatively equal distribution between the age of the existing building stock and the demolition of buildings constructed before 1950. In contrast, the distribution of demolitions for buildings constructed between 1950 and 1970 is much higher than these years of construction as a proportion of the existing building stock, while demolition of the newest buildings is very low. For Copenhagen (see Figure 11), there is also a very large demolition ratio of buildings built between 1950 and 1970, which is even greater than nationally. On the other hand, the demolitions of buildings built before 1950 are much lower than nationally. This may be related to the fact that in this construction period there are there many dwellings which in Copenhagen have a low demolition rate, whereas in Denmark there are a lot of old agricultural buildings built before 1950 which, according to Figure 8, make up a third of all demolitions in Denmark.

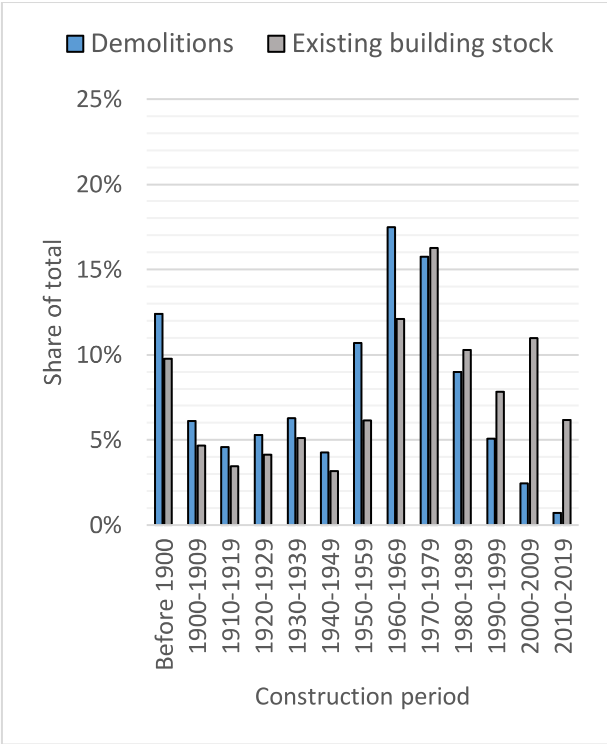

Figure 10. Demolition share from 2010-2019 in Denmark for different construction periods compared to the share of existing buildings from 2010-2019.

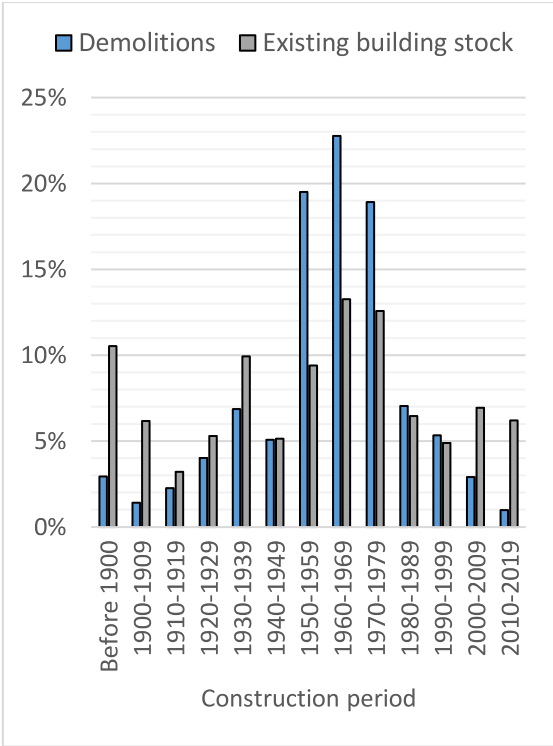

Figure 11. Demolition share from 2010-2019 in Greater Copenhagen for different construction periods compared to the share of existing buildings from 2010-2019.

The majority of all new construction in Denmark is for housing [110]. Since very few square meters of housing are demolished each year, even if all demolitions of housing in Copenhagen were avoided, would the demolished housing only cover 1.6% of the annual new constructed housing in Copenhagen (see Table 2). Nationally this amount is slightly higher, the preservation of housing through, for example, refurbishing possibly covering 8.7% of the annual need for new housing in Denmark. Due to the great demand for housing, the best design strategy will therefore be to maintain the function of the building through refurbishment. The same is the case for most other types of use, where typically more is built than demolished. In Copenhagen in 2019 six times more square meters were constructed than what is demolished, whereas nationally four times more square meters are constructed than demolished. This is partly due to a combination of higher demolition rates nationally together with the fact that the new construction rate is higher in Copenhagen. However, there are also some types of building use where the amount of annual demolished square meters is higher that the annual amount of new construction. Nationally this is the case for agricultural buildings, where the annual demolished floor area is 20% higher than newly constructed areas, indicating a minor potential for adaptive reuse by changing function. The big problem with changing the function of agricultural buildings is that the buildings are often located far from the cities and that the need for housing in the countryside is limited, drastically reducing the possibilities for adaptive reuse. Design principles must therefore focus on preservation of the function and thereby avoid demolition or utilizing the materials from demolition through recycling and reuse.

Table 2. Demolished and newly built buildings (in square meters) in Copenhagen and Denmark for various building uses and the potential to cover the need for new construction through building adaptation strategies.

	Copenhagen			Denmark		
	Demolitions (2018) [m²]	New construction (2019) [m²]	Demolition ratio of new construction	Demolitions (2018) [m²]	New construction (2019) [m²]	Demolition ratio of new construction
Housing	8,312	534,094	1.6%	295,166	3,380,672	8.7%
Agriculture	0	0	0.0%	627,483	527,250	119.0%
Commercial production	19,034	486	3916.5%	173,155	216,690	79.9%
Energy	1,319	65	2029.2%	10,216	48,187	21.2%
Transport	4,231	35,837	11.8%	22,478	179,593	12.5%
Office and warehouses	88,108	61,395	143.5%	390,321	898,212	43.5%
Hotel and restaurants	806	37,104	2.2%	21,002	101,208	20.8%
Culture	8	517	1.5%	8,799	20,971	42.0%
Teaching and research	2,832	39,954	7.1%	100,343	141,765	70.8%
Health	0	7,491	0.0%	1,193	41,712	2.9%
Day-care institutions	2,329	7,491	31.1%	30,452	41,712	73.0%
Leisure and sports	1,151	2,492	46.2%	76,858	283,317	27.1%
Garage & outbuildings	4,313	17,711	24.4%	160,971	1,427,426	11.3%
Total	**132,443**	**744,637**	**17.8%**	**1,918,437**	**7,308,715**	**26.2%**

In Copenhagen close to 80% of all new construction is housing, which means that most building uses related to various industries have higher demolition ratios than new construction. Most notable are commercial production buildings, where 39 times more square meters are demolished than are newly built, meaning that in principle the demolition of commercial production buildings could cover 3.5% of the need for new housing if demolition was avoided and the building was transformed instead through adaptive reuse. However, there can be big differences between how production buildings are built, many of which will therefore probably not be suitable for typical housing layouts. Likewise, more square meters are demolished than are newly built within energy supply, but overall this accounts for only a very few square meters, and the potential is therefore very limited, while the typology probably also differs a lot from housing. One building type that typically has a structure similar to residential buildings is the office. In Copenhagen, 43% more square meters were demolished in 2018 than the square meters of new constructed offices in 2019. The office is also the type of building that is demolished the most in Copenhagen, but since there is also a great demand for new offices, the majority of the demolished square meters could be preserved through refurbishment instead of adaptive reuse. The remaining 43% will potentially cover 5% of the annual need for new housing construction in Copenhagen.

5.3. Understanding the dynamic life-cycle of buildings through better lifespan predictions of existing building typologies

The lifespan of buildings can either be calculated as the total lifespan between construction and demolition or as the building's service lifespan (or service life), which denotes the period during which buildings are functionally operational and therefore does not include any vacancy periods. The typical lifespans for buildings in Denmark are mainly orientated towards the building’s use, where housing that is up to Danish standards has an expected average lifespan of 120 years, an agricultural building has an expected average lifespan of 40 years, and office buildings have an expected average lifespan of 80 years. On the basis of Figures 8 and 9 in the previous chapter, it makes good sense that the differences between building use and the expected lifespans match closely the fact that the types of building use that have a high demolition rate often also have a shorter lifespan. From Figures 12 and 13, it is clear that demolition is not only determined by age because it is distributed very differently over different construction periods. Some of this difference can be attributed to the fact that in some periods many more square meters were built, such as from 1960 to 1980, which is also reflected in the fact that they make up a large part of the demolitions. However, many dwellings were built during this period which, according to our standard lifespans, should have an average lifespan of over 120 years.

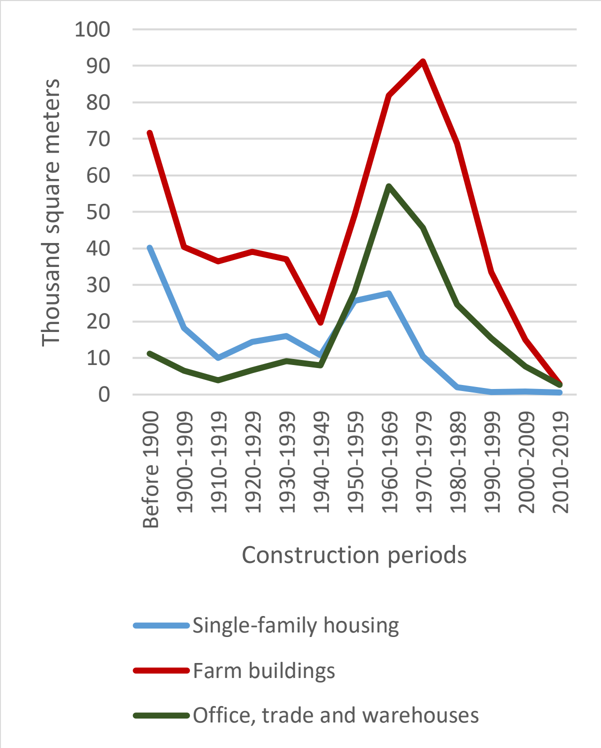

Figure 12. Average demolished square meters from 2011 to 2019 for different building uses divided over different construction periods.

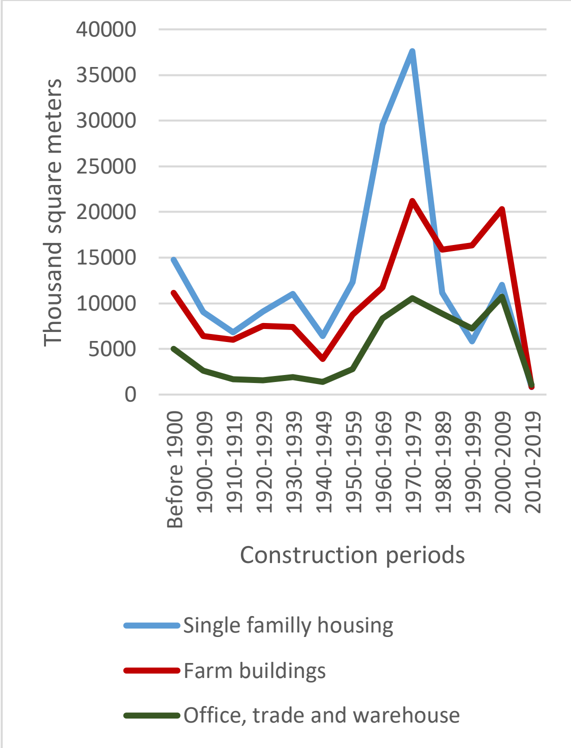

Figure 13. Square meters in the existing building stock in 2011 for different building uses divided over different construction periods.

If the figures for demolitions are area-corrected in relation to how much the building type makes up of the existing building stock (see Figure 14), it is clear to see that there is a large peak in demolitions of offices built around 1950-1959, and that for farm buildings in general there is a peak in the demolition of all agricultural buildings built before 1990. At the same time, the demolition of single-family houses is relatively evenly distributed over the period before 1959, after which there is a large drop down to a demolition rate close to 0%. With the current lifespans of buildings being static for both new buildings and old ones, there is a risk that the results in LCA and LCC calculations do not reflect the actual dynamics of the lifespans of existing buildings. This can therefore lead to the remaining lifespan in existing buildings being either underestimated or overestimated when we use the same lifespans for all construction periods. There is therefore a need to update and expand the lifespans in Danish standards to include different construction periods for all building uses.

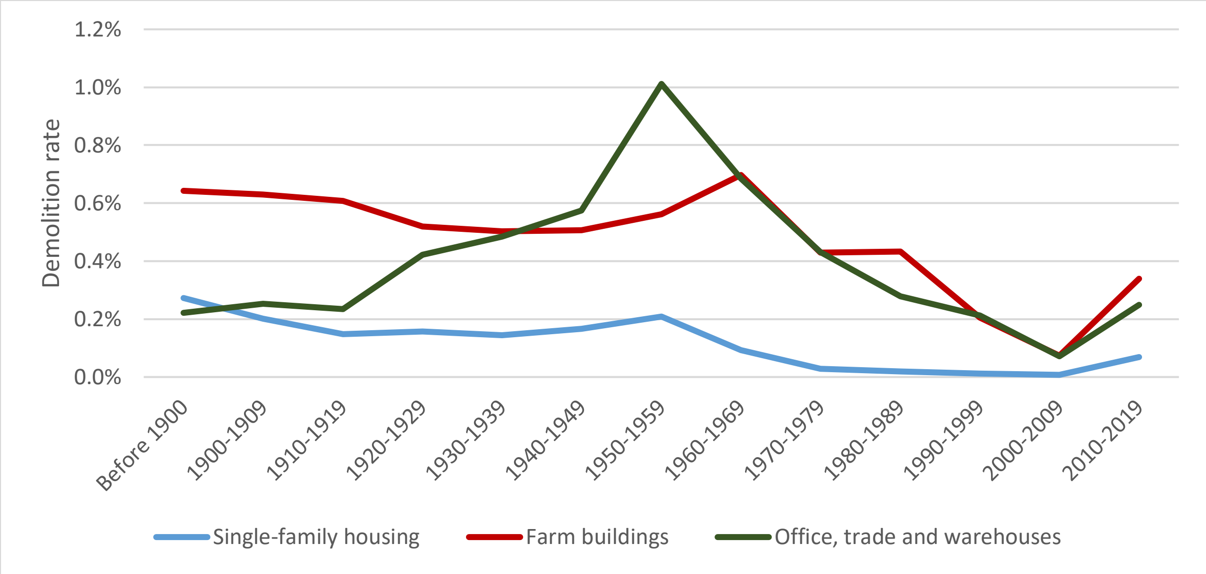

Figure 14. Area-corrected demolition rate for single-family, agricultural and office buildings.

The lifespan of buildings can be calculated in several different ways. The method used to calculate standardised lifespans in Denmark is relatively simple and assumes that the demolition starts after about ten years from when the building was constructed, after which the building stock from that construction period is reduced linear by a demolition rate of 0.5%, 1% or 2% [125]. Figure 14 clearly shows that demolitions do not happen linearly. When half of the building's stock for a particular building use has been demolished, that defines its lifespan. The problem with this method is that, when all construction periods are collected in the same lifespan, but this does not take into account that some construction periods have significantly more buildings constructed, so that these construction periods become defining for the lifespan of all buildings with the same use. Another, simpler method to estimate lifespans is to calculate the average age of the buildings being demolished. However, this does not include all the buildings that are not demolished, which make up the vast majority of buildings. A third way to calculate lifespans is therefore to assume that the demolitions for a certain construction period over time can be described via a Generalized logistic function because demolitions behave like an S curve (also known as a Richards curve). The principle is that in the years after a building is constructed, there is a relatively small risk of it being demolished because it performs highly in terms of its technical, functional, architectural or economic value. At some point, the building deteriorates technically or is no longer architecturally attractive, thereby creating a risk of demolition if it is not renovated or transformed. When all the buildings from the same construction period reach this point, there will be a large increase in demolitions. At some point, the majority of the buildings from the construction period will have either been refurbished or demolished, and the demolition rate will therefore level out, which is probably what has happened for office buildings built before 1940 in Figure 14. By analysing data for the 124,084 cases of demolition obtained from the BBR, it is possible to 'fit' the historical development to the S-curve in order to determine where in the process the various existing buildings are in relation to the background of building use and the construction period. This makes it possible to calculate both the average lifespan and the remaining lifespan for different construction periods.

In general, multi-family buildings are the type that is demolished the least. This is also reflected in the lifespans, multi-family buildings having the longest average lifespan, which is around 227 years. However, there is a very large difference between the older and newer construction periods (see Figure 15), which means that newer multi-family buildings built after 1990 have an expected average lifespan of 168 years, which is about 48 years higher than the standard lifespan of 120 years for housing that is typically used in LCA calculations in Denmark.

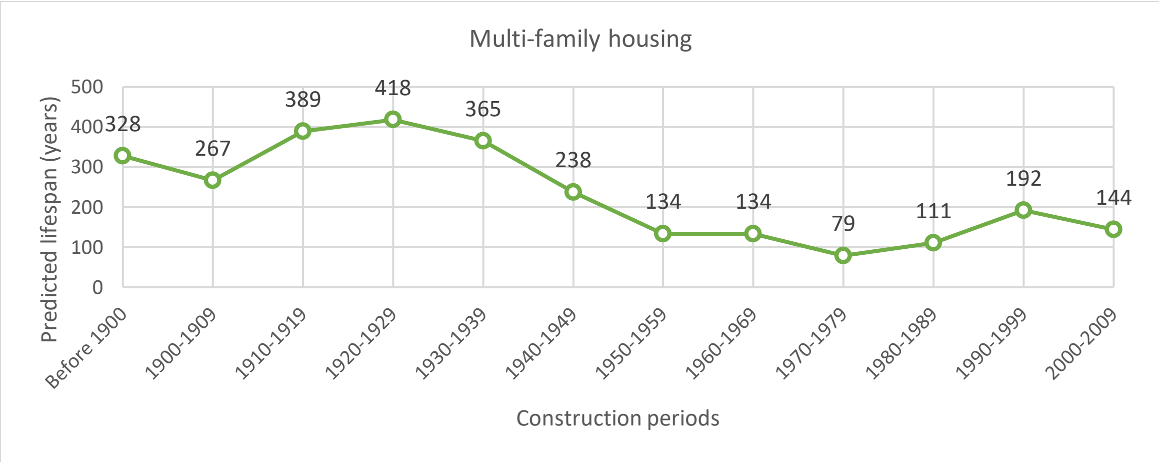

Figure 15. Predicted average lifetime for different construction periods for existing office buildings in Denmark.

Conversely, single-family housing (see Figure 16) from the same construction period has an expected lifespan of 77 years, which is 44 years lower than the standard lifespan of 120 years, but the average for all construction periods for housing is 129 years and therefore only 9 years higher. However, the very few demolitions of multi-family buildings means that there are very few data points for that building use, meaning that the estimated lifespan of multi-family housing is associated with greater uncertainty than other types of building use. Conversely, single-family houses account for around 20% of all demolished square meters and are therefore associated with less uncertainty.

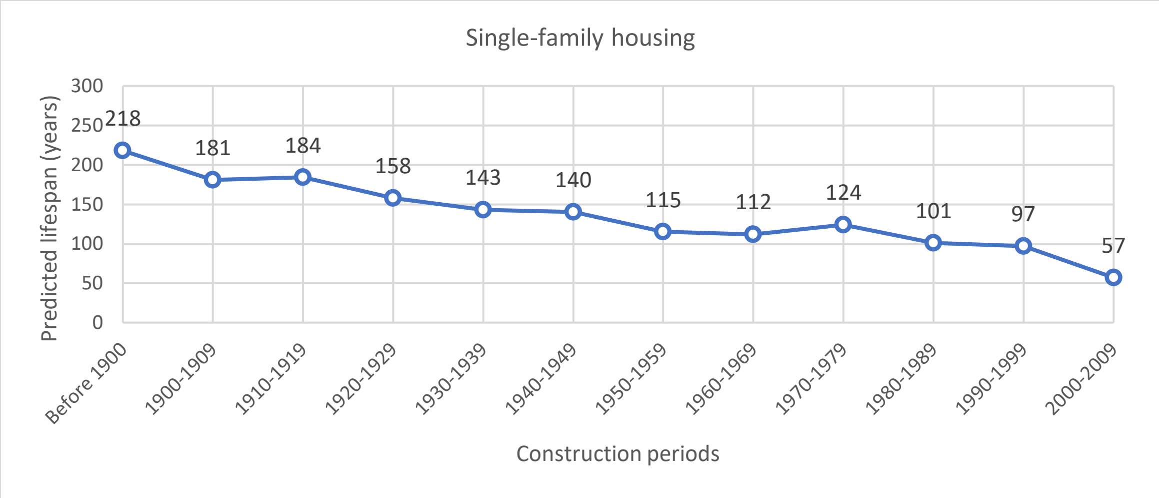

Figure 16. Predicted average lifetime for different construction periods for existing buildings used for single-family housing in Denmark.

For office buildings (see Figure 17), as with single-family housing, there is a tendency for the expected lifespan to fall the newer the building is. The newest office buildings built in the period from 2000 to 2009 therefore only have an expected average lifespan of 37 years, which is less than half the lifespan of the 80 years that is normally used in the Danish standard for lifespans for office buildings. There are therefore only buildings built between 1950 and 1969 that fit the Danish standard, whereas buildings built before 1950 often have an expected average lifespan that is considerably longer than the 80 years.

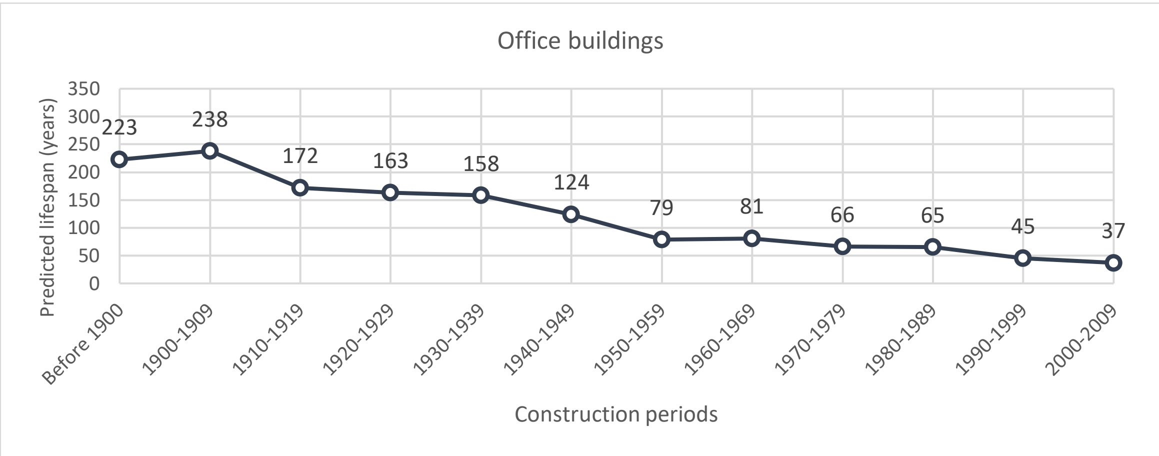

Figure 17. Predicted average lifetime for different construction periods for existing buildings used for multi-family housing in Denmark.

The lifespans of buildings are one of the most uncertain parameters in LCA calculations and can therefore have a large impact on the results of such calculations. This is because, for a building with a long lifespan, the materials for construction will make up less of the total impact, whereas energy will make up a larger share of the impact. LCA has until now focused a lot on new construction, and therefore many of the lifespans we use today are focused on new buildings and can therefore be very misleading for existing buildings from different construction periods.

5.4. Demolition processes

At present, there is very limited knowledge about selective demolition processes (as identified in Knowledge gap 2), partly because research is more focused on what happens before (refurbishment) or after (new construction) the demolition. Through collaborations with demolition companies, it has been possible to obtain data on both conventional demolition processes, as well as data from case studies of selective demolition processes. This chapter will describe how selective demolition differs from conventional demolition in both processes and its possible environmental impacts.

5.4.1. The conventional demolition

The use of time-effective heavy machinery is probably what describes conventional demolition the best. Before the start of conventional demolition, a pre-demolition audit is carried out, partly to establish which materials the building consists of and their expected waste treatment, but also to investigate whether harmful substances such as asbestos, PCBs, chlorinated paraffins or heavy metals are present in the building parts. This pre-demolition audit must be submitted to the municipality no later than two weeks before the start of the demolition. If the building consists of building parts with large amounts of harmful substances (typically windows, joints, paint or asbestos parts), these parts will most often be removed via a remediation process, which may involve both manual removal or removal via sandblasting or other cleaning.

Figure 18. Demolition of the load-bearing concrete frame for an old office building in Carlsberg Byen. Note the freestanding water vaporizer at the bottom, as well as the water vaporizer mounted on the demolition machine to avoid dust.

Technical installations and cables will typically also be removed manually, since these elements contain high-value metals. After this, the basic building consisting of the load-bearing parts will usually remain and be demolished by heavy machines or, in rare cases with high-rise buildings, by explosion. These demolition machines, which are large excavators, have a grab that can take down and coarsely sort building parts, as well as a mounted water vaporizer that prevents the formation and spread of dust. There will typically also be several external water vaporizers located in different places on the demolition site. Based on data from the demolition companies, such a demolition machine can demolish and roughly sort around 7.1 m^2 of building floor area per hour, while the water vaporizers use around 2400 liters of water per hour, depending on the size. If there are still materials in the building that contain harmful substances, such as concrete with PCBs, this will be removed separately and handled as hazardous waste. At the demolition site, the clean materials must be sorted into ten different waste fractions, namely 1) natural stone, 2) unglazed tiles, 3) concrete, 4) mixed natural stone, unglazed brick and concrete, 5) iron and metal, 6) plaster, 7) rock wool, 8) earth, 9) asphalt and 10) mixed concrete and asphalt. If the amount of waste does not exceed one ton, as is typically the case for minor renovations, there is no requirement for sorting [112].

Figure 19. Conventional demolition of office building. The windows and fixtures have been removed in advance, but the remaining building parts will be demolished and sorted on site.

The demolition waste is then either transported to a sorting facility or sent directly for recycling, other recovery or disposal. Recycling covers the handling processes whereby waste materials are reprocessed into new products. The designation ‘other recovery’ is used for waste materials that are used for backfilling and thereby replace either soil or gravel, as well as waste materials that are burned in connection with the production of electricity or district heating. Disposal covers fifteen different waste-management processes where there is no value associated with waste management as there is with recycling. Disposal therefore covers different types of landfill, discharge of waste water into the sea, biological purification or incineration without energy utilization. When the construction waste leaves the demolition site, the demolition process officially ends, and the material now enters the waste-treatment processes mentioned above.

5.4.2. Selective demolition

Selective demolition differs from conventional demolition by having a greater focus on preserving a high value for the materials and components, typically with the aim of subsequently being able to reuse them in new construction or renovation. In order to avoid damaging the building components during demolition, it is necessary to replace the heavy machinery from the conventional demolition with manual labour and lighter tools when dismantling the building. Here, the components are removed manually with either electric screw drivers or cutting tools. To gain access to the building components, scaffolding (see Figure 20) or mechanical lifts (see Figure 21) are often needed. However, when selectively taking down taller buildings or roof structures, heavier machines such as cranes must also be used. At the same time, the removed components typically also have to be packed and transported around the demolition site by forklift trucks and finally loaded onto trucks for transport to storage or transported directly to a new site.

Figure 20. Selective demolition of roof tiles using scaffolding (photo provided by Tim Riis Tolman, Lendager TCW).

At present, there are no national statistics on how much of the construction waste is reused. Since only 36% of Danish construction waste was actually recycled in 2019 [25] and 52% of the construction waste was 'other recovered' [25], it is probably a very small part of the waste that is reused. A case study of the selective demolition of two buildings from 1921 and 1967 that was investigated in connection with this PhD project showed that it was mainly bricks, roof tiles, roof trusses, external paving stones, window sections and metal façade cladding that could be manually taken down and reused, whereas remaining concrete structures, such as foundations or the load-bearing structure in the building from 1967, had to be subsequently demolished conventionally with crushing. Although the building part is detached manually, there may be various loss percentages for the taken down building parts because they are either in poor condition or have been damaged during removal and therefore cannot be reused. In the case study, it was found that the use of angle grinders rather than screw machines had a large impact on the waste percentages for removed façade cladding [126].

Figure 21. Selective demolition of façade cladding using a mechanical lift (Photo provided by Tim Riis Tolman, Lendager TCW).

To selectively demolish bricks manually is also unrealistic in larger quantities because it is so time-consuming. Because they are composed of mortar, therefore excavators must also be used to topple the walls, which meant that in the case study there was a waste percentage of 30% of the bricks taken down which could not be reused. The roof tiles that could be removed manually, on the other hand, only had a waste rate of 15%. The big problem with selective demolition is therefore that, if the waste percentages are to be kept down so that the building components are reusable, machines must be used as little as possible and replaced with more manual work, which makes selective demolition much more expensive than conventional demolition. An important prerequisite for large-scale selective demolition is therefore that it becomes possible to sell the reusable building components at the same price or a lower price than products based on virgin materials. Again, it is especially the time-consuming processes in the demolition that determine the price of reused materials, especially because the price of labour is high in Denmark and the fact that manual work is taxed higher than bought products. The case study of the selective demolitions therefore showed that the selective removal of roof trusses was not economically advantageous because there were very large costs for wages during the removal, since there had to be ten people involved in the removal at the same time, and rent had to be paid for a mobile crane to lift the rafters down without damaging them [127].

6. Part 3: Assessment of circular design strategies

This chapter will examine how the potential for the transformation of existing buildings through adaptive reuse can be assessed and visualized and how this can be used as a tool to create a focus on circular design strategies in urban development. At the same time, there will be buildings that are not suitable for transformation because they have a structure or location that does not make it environmentally or economically advantageous to avoid demolition. Therefore this chapter will also examine the environmental benefits and technical challenges of circular reusing materials from selective demolition.

6.1. How to measure, assess and visualize the transformation potential of existing buildings

6.1.1. Transformation potential vs transformation capacity

Demolitions are often driven by changes in need, whether it is a desire for more floor space, other building functions or a decreasing demand for builds. The analysis of demolition and new construction patterns in the previous chapter showed that large amounts of industrial buildings are being demolished in the cities, and that housing in Denmark now accounts for around 80% of the square metres newly built annually. An important design principle for reducing the amount of demolition in the cities is therefore to change the function of the existing industrial buildings to housing through adaptive reuse. Whether the building is suitable for changing function at all can be assessed by looking at how flexible the building is in relation to it being able to fulfil the new required functions. This could be, for example, flexibility in relation to room heights so there is space for ventilation ducts, dividing rooms in relation to the floor layout, or options for expanding the capacity of technical installations. Flexibility can be calculated on either the component, building or location level, but if the purpose is to assess an existing building's flexibility so as to change its function through adaptive reuse, it can be defined as ’transformation potential’. If the purpose is to assess the building’s future flexibility (its ability to incorporate future changes), it can be defined as ’transformation capacity’. It is therefore often the transformation capacity that is in focus when flexibility is implemented in new buildings or after refurbishment projects as a circular design strategy, whereas the transformation potential is involved when flexibility in existing buildings is utilized, for example, in connection with a conversion from industry to housing. This chapter will focus particularly on the transformation of the existing building stock through adaptive reuse and therefore mainly the transformation potential.

6.1.2. Visualizing the transformation potential of buildings

Some of the first in-depth studies of flexibility in construction were carried out by the Dutch architect N. John Habraken around 1961, to which he gave the term ‘open buildings’ [128]. Habraken’s studies were in-depth analyses of which parameters had an impact on how flexible buildings were, but they were not tools that could measure or calculate the degree of flexibility. In connection with the greater focus on a restructuring of construction, there has also been more focus on how flexible our buildings are, and several tools have been developed that can measure the degree of flexibility in relation to adaptive reuse [129–131] and future renovations [132,133]. These tools often contain a large amount of building indicators, which can be an obstacle to usability because it can be time-consuming and expensive to collect data on so many indicators. Sustainability certifications such as the DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen), BREEAM (Building Research Establishment Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design) or the Nordic Swan Label are given to many larger new building projects in Denmark today. DGNB and BREEAM also contains indicators and criteria for flexibility in relation to ceiling heights, floor plans, and access to and the capacity of systems and installations. These flexibility indicators are therefore some of the most widespread indicators that are currently used to define and measure flexibility in new buildings. It therefore makes good sense to use the DGNB indicators and criteria as a basis for measuring flexibility in relation to existing buildings. The previous tools (and partly DGNB) have mainly focused on the flexibility of new buildings in relation to future transformations or their flexibility in relation to future dismantled components and materials for reuse and recycling. Because the function of the building has a large impact on whether a building will be demolished, it is important to have tools available in the early planning phase that can quantify and visualize the possibilities of preserving the building through adaptive reuse. Rob Geraedts from the Delft University of Technology [130] has already developed a tool that can be used to assess the potential for transforming old office buildings into housing. The transformation potential is calculated on the basis of a total score of 23 indicator criteria at the area level and 28 indicators at the building level. However, this tool only measures flexibility in relation to one type of conversion, whereas, in connection with planning transformation in urban development, it can be advantageous to measure flexibility in relation to the transformation of several different building types. As previously described, one common feature of many flexibility tools is that they generally use a very large number of indicators and criteria for assessing flexibility and transformation potential. Since it is often difficult to obtain data on existing buildings, this may mean that a very comprehensive review of the building's layout, constructions and installations must be carried out first, which can make it difficult to use the tool as a fast and cost-effective screening tool. In order to test data availability and opportunities to expand the options for measuring transformation in relation to several building functions, two tools were set up in the project to calculate and visualize flexibility in adaptive reuse. The tool was selected with criteria that made it possible to calculate the potentials for adaptive reuse in relation to 'office', 'teaching', 'residential', 'hotel' and 'trade', mainly based on DGNB criteria (see Table 3). In order to examine the necessary criteria needed to calculate the transformation potential, the tool was designed in two versions, whereby the first version tested a broad set of 64 indicators [134], the second being a light version with a selection of the twenty most used indicators from previous studies [135].

Table 3. Example of five indicators in the transformation potential 'light' tool with associated building-specific criteria based on DGNB. Table adopted from [135].

Indicator	Use	High transformation score (1)	Middle transformation score (5)	Low transformation score (9)
Dimensions & Flexibility				
1) Free room height measured from floor to ceiling	*Same for all*	≥ 3.00 m	≥ 2.6 m	< 2.60 m
2) Building depth from exterior wall to exterior wall	*Office*	12,50 m ≤ building depth < 14,50 m	10,00 m ≤ building depth < 16,50 m	10,00 m > building depth > 16,50 m
	Educational	-	-	-
	Childcare	-	-	-
	Housing	building depth < 11.5 m	11,5 m ≤ building depth < 13,5 m	building depth ≥ 13,50 m
	Hotel	12.5 m ≤ building depth < 14.5 m	10.0 m ≤ building depth < 16.5 m	10.0 m > building depth > 16.5 m
	Shops	-	-	-
3) Corridor width	*Same for all*	Corridor width ≥ 1.80 m	Corridor width ≥ 1.5 m	Corridor width ≥ 1 m
4) Window proportion of the façade	*Same for all*	< 20%	< 40%	≥ 40%
5) Distance between technical shafts	*Office*	< 20 m	30-20 m	> 30 m
	Educational	< 20 m	30-20 m	> 30 m
	Childcare	< 20 m	30-20 m	> 30 m
	Housing	< 10 m	10-15 m	> 15 m
	Hotel	< 10 m	10-15 m	> 15 m
	Shops	< 20 m	30-20 m	> 30 m

A test of both tools on a case building (see Figure 22) of an office building transformed to student housing showed that there was no great difference in the results between the two tools when measuring and visualizing the transformation potential. Therefore the number of indicators can be advantageously reduced to make the tool more usable.

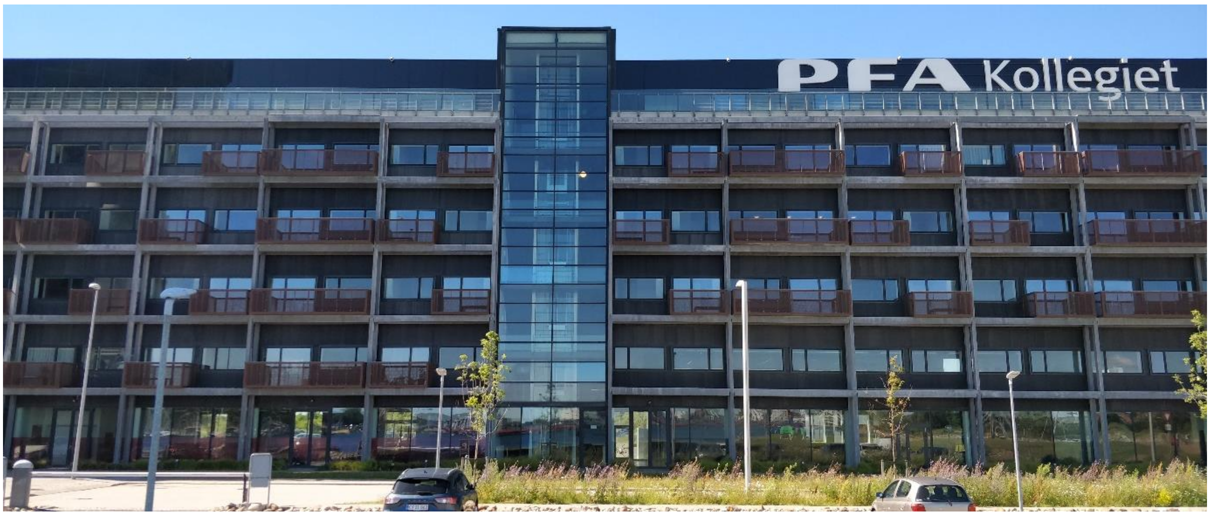

Figure 22. Sample building used for testing the transformation potential tool. The building was constructed in 2002 as an office building and was transformed into a dormitory in 2020.

The testing of both tools also showed that the building had the most transformational potential in relation to offices, which makes sense, since the building was originally designed as an office. This also shows the advantage of preserving the function of buildings for as long as possible because it will require the fewest changes.

6.1.3. Visualizing the transformation potential in urban development

The existing tools may be applicable at the building level, but in the case of the transformation of urban areas it can be difficult to screen many buildings at once simply because collecting data on many buildings will be too expensive. There are several situations where the mass screening of transformation potentials on urban areas can be relevant. The first situation could be a company or a public authority that needs to construct a new building. Instead of buying the building first and then demolishing it, a pre-screening of several buildings will enable the company to focus on buildings that either already have the desired specifications or buildings in which they can be transformed into the desired specifications and thereby avoid demolition. An example could be an authority needing to build a new school. Instead of looking for building plots with buildings that will then have to be demolished to make way for the construction of the school, the authority can look for buildings that already meet the defining criteria for whether they can be transformed into a school. Another example is a property investment company that will build new housing where a pre-screening of several office buildings for sale will be able to identify the building that is closest to the desired layout for the new apartments. This can potentially prevent the demolition of buildings because it becomes easier to visualize their possibilities for transformation and at the same time choose the transformation strategy that best suits the building at risk of demolition. Another situation where the pre-screening of several buildings can be relevant is in relation to the initial planning and design phases of large urban development projects. When the municipality issues design competitions for the development of large areas with many, often existing industrial buildings, requirements for the preservation of buildings have often been defined by the

SAVE value. However, a pre-screening of the transformation potential will potentially give the municipality a better opportunity to make demands for which buildings must also be preserved from a transformation point of view. This may happen if, for example, they are assessed as having a high potential for transformation in relation to some of the uses that are desired to be incorporated into the urban area. Based on the MCDM (Multi-criteria decision-making) method, on which the DGNB is also based, it is potentially possible to make an overall assessment of the best conservation strategy for an area because it enables the assessment and comparison of many criteria in the same analysis. By also using MCDM methods such as TOPSIS (technique for order of preference by similarity to ideal solution), it will also be possible to distinguish between the anti-ideal (everything will be demolished) and ideal (as much as possible will be preserved) situations for the area. In order to be able to do large pre-screenings at the area level, however, the necessary data must be available. Although Denmark is among the countries that has the most data available on existing buildings, the test of the transformation tool showed that there are still many shortcomings in being able to automate the acquisition of data for assessing transformation potentials. One of the biggest obstacles is the lack of digitized data on dimensions that often have to be found in drawing materials. Many of the most relevant criteria for transformation and flexibility are the internal dimensions, such as room heights, room divisions, distances to access roads and building depths. All this data can be found at the building level, but it will require so much processing that large pre-screenings of transformation potential at the area level do not currently seem economically feasible.

6.1.4. Improvements and recommendations for assessments of transformation and flexibility

There is currently very limited data available on the internal layout of the buildings, and even if the digitalization of the building stock is improved with publicly accessible BIM models or building passports, much of the important data still cannot be automatically extracted from the models, as different internal measurements form a barrier. There may also be several conditions in relation to flexibility which are based on assessments because they are currently difficult to measure, such as the ratio of floor utilization. However, measurements are often made in connection with the preparation of energy labels, but since it is only the surface areas of building parts that are indicated on the energy label, it is not currently possible to access the measured information. It is also important to have a discussion about registration requirements in relation to how much value can be obtained from the analyses, because registering data can be very difficult and expensive both for those who have to register the data and those who have to manage it. Therefore, it is important to ensure that future registration requirements for building data can provide data for a wide range of different analyses in order to justify the additional registration burden. There is therefore a need for future studies that try to identify and group urban analyses in relation to circular potentials so that it is possible to determine which data requirements are necessary and where in the analyses there is data overlap.

Most current flexibility and transformation tools are based on a points system which calculates an overall score for the transformation potential or capacity. This was also the case for the transformation tool that was developed and tested in this project. However, subsequent conversations with architects, urban planners and engineers have made it clear that some criteria are more defining as to whether a building can be transformed, such as the internal ceiling height, the load-bearing capacity of the static system, the presence of harmful substances, or the location of the building on the plot in relation to building percentages. A future development of methods for calculating transformation and flexibility can therefore be based on knockout criteria instead of an overall score. Alternatively, weighting can be introduced in relation to the importance of the criteria for transformation, but here it is also difficult to take into account conditions which in practice make the transformation impossible, such as hazardous substances and limited room height. A final option is to have a pre-scan with knockout criteria, after which, if the building is still suitable for transformation, a weighted point-based analysis of criteria can be made that may complicate the transformation but not necessarily prevent it, as with the knockout criteria. However, more research is still needed into which criteria are the most defining or limiting for whether a building can be preserved through adaptive reuse.

When around 80% of all new construction in Copenhagen is residential, there is a high chance that industrial buildings will be transformed into housing. Many industrial and agricultural buildings at risk of demolition have a layout or a location that does not make them suitable for transformation into housing. On the other hand, there may be cultural applications like museums or conference halls where large industrial buildings can easily be transformed due to their large open layouts. However, many office buildings have small room divisions that are suitable for smaller apartments for student housing. In order to be able to target the transformation and flexibility analyses, there is a need for studies that group different building types on the basis of building specifications and layout. The reason why it is important to group building types is that the transformations that are the most environmentally friendly and cheapest are those where the fewest possible changes must be made in connection with the transformation. If an office building with many small rooms is transformed into a dormitory, this means that there will often be a minimal need to demolish and add new interior walls, whereas an atrium office building will require the insertion of many new walls and is therefore more suitable for larger apartments. At the same time, there will also be many building types where it will not make sense to measure the transformation potential (e.g. small one-storey garages or sheds that are transformed into cinemas), because the building specifications and layout are too different. A grouping of transformation potentials can therefore target the analyses so that only the relevant buildings are assessed. This will also be able to justify the large data requirement for the analyses because the number of buildings that must be assessed is drastically reduced, since the transformation potential is only calculated on buildings that are real realistic alternatives within adaptive reuse.

6.2. Circular reuse of components from selective demolitions

Adaptive reuse of buildings can be considered a direct reuse of building components on site. This requires minimal processing of the materials and should always be preferred. However, there are buildings which are not suitable for adaptive reuse and which are very difficult to avoid demolishing. Here it is important that selective demolition is carried out (see section 5.4.2.) in order to obtain the highest possible environmental value from the materials and establish the possibility of being able to reuse them again, either in a new building on the same site, in a new building or in refurbishing an existing building off site. This chapter will describe the work that has been done in connection with creating more knowledge of the environmental benefits and technical challenges of reusing building components from selective demolition.

6.2.1. Environmental benefits of reusing components

Some building components from selective demolition are in such good condition that they can often be reused directly after they have been taken down and packaged. The environmental impact of using direct reuse will therefore be minimal and mainly based on the processes that occur in connection with the selective demolition. Conventional demolition, where large machines are used to crush the building quickly and sort the materials, is very similar for the various building components, and the most defining factor in relation to the environmental impact is how much material must be demolished and thus the time the demolition machine must be in operation. Since water vaporizers are used in conventional demolition to avoid the spread of dust (see Figure 18), there will also be an environmental impact from water consumption, but even if a water atomizer uses about 40 litres of water per minute [126], the environmental impact of water consumption is minimal in a country like Denmark, where water is not a critical resource. In the selective demolition process, the environmental impact is much more influenced by dismantling methods and the time required to take down the various building components. The roof tiles can be taken down manually using scaffolding, which means that the environmental impact from the operation of machines is very small. On the other hand, roof trusses must be taken down with cranes, which means that one or more heavy machines must be operated for a long time per component. The same is the case for windows or façade cladding, where both lifts and telescopic loaders must be used to be able to access and remove the components, so that the operating time of the vehicles is longer than with conventional demolition of the façade cladding. Reuse of bricks may also require the walls to be knocked down with an excavator, which can have a major impact on the loss of bricks that cannot be reused. Subsequently, the bricks must be prepared for reuse, being cleaned and sorted either on site or transported for off-site cleaning. The longer time consumption of machines can therefore mean that the selective demolition process of some building components itself has a greater environmental impact than the corresponding conventional demolition process. Moreover, the waste percentages in the selective demolition can also have a large impact on how much of the material can be reused.

When the building components have been demolished through selective demolition, they often have to be prepared for reuse. Which form of preparation is chosen can have a major impact on the future life of the product. In the example of reusing steel façade cladding, the architects' decision was that only a basic cleaning of the removed cladding should take place, with the arguments that the panels should both look reused and that the environmental impact of sandblasting and repainting was assessed as too great. However, the expected lifespan of the reused façade cladding depends on the condition of the steel panels. If the steel panels are sandblasted and repainted, they have an expected lifespan that is equivalent to new panels. In addition, losses in the selective demolition can also be reduced because façade cladding that would previously have been discarded due to its visual condition or damage to the coating can then been reused instead of becoming waste. The LCA calculations of the scenario with façade panels that were sandblasted, zinc-coated and repainted also showed that there was still an environmental saving in the preparation. This was because of the basic saving of the production of virgin steel for new panels, since the process of zinc-coating and painting happens in both cases. This study of the reuse of façade cladding shows that it is important to map the processes of reuse scientifically and calculate the future derived environmental savings in order to be able to make the best choices in connection with the reuse of components from selective demolitions. If there is insufficient documented knowledge of the processes in connection with the reuse of building components, there is an increased risk of choices being made on the basis of good intentions to reduce the environmental impact in either the selective demolition process or in the process of preparing the product for reuse. However, this will actually limit the possibilities of reusing the components again at a later date if the entire lifespan of the product is considered.

6.2.2. Problems and obstacles in the circular reuse of components

Although there can be environmental benefits in reusing building components, selective demolition with subsequent reuse is currently performed in very limited quantities. There are no statistics on how much of the construction waste is reused in Denmark, but in relation to the fact that only about 32% was recycled in 2020 [23], reuse probably only constitutes a very small proportion of all the construction waste. Based on the work with waste data, case studies of selective demolition and conversations with actors such as the demolition company, authorities, contractors, engineers and architects, four current obstacles to implementing more reuse have been identified:

Technical possibilities for reusing. One of the major limitations is the ability to demolish the components technically in a format in which they can be reused in conventional construction. In the case study of a selective demolition, not all materials could be separated and thereby reused. There was therefore still a large amount of material that had to be disposed as waste. One of the largest quantities of waste materials in this case study was concrete. In construction, concrete structures can either be cast on site or cast as elements that are assembled on the construction site. Common to both types, however, is the fact that they are moulded together, which makes it difficult to take them apart again in connection with a selective demolition in a format that can be used in accordance with the standard dimensions used in construction today. In addition, there are also challenges in relation to being able to document the strength of the reused concrete, which means that concrete is typically crushed and in some cases recycled as aggregate to produce new concrete. The problems of reusing concrete can be solved for new buildings by making concrete that is designed in standard sizes for separation via fittings, a method that has been used in Finland for many years because it can be difficult to cast concrete elements together due to the cold weather conditions [136]. However, concrete in old buildings is not designed for separation, and therefore it can be difficult to make any real reuse of concrete from existing buildings where the concrete also subsequently has a static function. Building components such as windows can be relatively easily detached from the old building in a selective demolition, but here the technical obstacle is the technical properties of the window, which are often considerably worse than the energy requirements for new windows in relation to heat loss. In order to meet the requirements, it may therefore be necessary to change the windows by replacing the glass or combining several windows. It is therefore technically possible to upgrade the windows, which will mean that the environmental savings of the reuse will be less because extra materials often have to be added to maintain the function of the component.

Harmful substances in existing buildings. Just as it can be a challenge to transform an existing building if it contains many harmful substances, the same applies in relation to the reuse of components from buildings that are contaminated. Some harmful substances are only present in the components where they were originally used, as is often the case with lead-containing paint or chrome, copper, and arsenic in impregnated wood. Asbestos in Eternit sheets, ceiling sheets or fire insulation can pose a serious health risk in connection with the selective demolition. PCBs from seals can migrate into other components and contaminate them, which means that materials that would otherwise be suitable for reuse suddenly cannot be reused because they now contain PCBs. In relation to reuse, many of these harmful substances are a major limitation in relation to how much reuse can be implemented. For example, PCB was used from 1950 to around 1970, the period in which most demolished buildings were constructed. There are several technologies under development to remove harmful substances from building components, which may mean that more components can be reused in the future. The methods include sanding, sandblasting or heat treatment, but because many of the methods and technologies for cleaning components are still under development, there is great uncertainty about the effectiveness and the environmental impact of these methods if, for example, components must be heated to high temperatures, or the cleaning results in a large proportion of damaged components.

Economy and preservation of value. Because the reuse of components often means manual selective demolition, it can be very costly to dismantle reusable components. This is partly because costs for salaries are high in Denmark, partly because salaries are taxed at around 50%, whereas the tax on consumption is only 25%. If it is also necessary to process the components afterwards in order to be able to reuse them, there will also be an additional cost for salaries and materials, which can contribute to the reused building component being much more expensive than buying a new conventional product. Because it is costly to reuse, a solution with a lower economic and functional value is often chosen. An example could be wooden floors that have been selectively demolished, but instead of being reused as wooden floors again, they are ‘down-cycled’ by being cut up into small pieces and used for wall cladding or other types of decorative use which is not similar to the original function. In Denmark this is often referred to as reusing or up-cycling, but because the smaller pieces of wood cannot fulfil the same purpose as the original function, in principle they have less future circular and economic value. There is therefore an important task in disseminating more knowledge about the importance of keeping materials and building components at the highest possible value level for as long as possible, since over the product's service life it will provide the greatest environmental savings and potentially enable multiple life-cycles of reuse.

Traceability and time aspects. The last major challenge in relation to increasing reuse is the working methods and techniques that are used in construction today. It can take years or months to design and plan a new building and then around a year to build it. Design choices in relation to materials and components must be made early in the design and planning process. Here, the implementation of reuse is a big challenge today due to the relatively limited volume of components that are available for reuse. As a result, it is difficult for the designers of a building today to know whether, a few years into the future, there will be sufficient quantities of reused components available, with the desired visual expression and with the desired technical properties. To remedy this problem, it may be necessary to have large storage areas where the reused components can be stored until they are to be used. However, it does not seem economically feasible to store such large quantities of components for several years, and since many components must also be protected from the wind and weather, huge halls may also have to be built for storage, which can also cause financial and environmental challenges. Since large numbers of agricultural buildings are being demolished, one possibility may be to take down and reuse large agricultural buildings for the storage of components. Another option to avoid having to store the components for several years is to establish collaborations between the property owner, the demolition companies and the construction company. In this arrangement, a property owner who has plans to demolish a building can make a contract with a construction company to sell the components as reused directly to the construction company when the building is demolished. In this way, a direct transfer of components can take place, and the property owner and the demolition company also have an incentive to obtain as much reuse as possible from the demolition. Often, however, buildings are demolished soon after a sale, and thus a timely agreement cannot be made between the property owner and the construction company. It is therefore likely that in the future recycling will be based on a combination of both storage sites and such collaborations.

6.3. Implications for the construction industry and future development opportunities within circularity

The four knowledge gaps identified in chapter 2 have been elaborated and analysed throughout the thesis, which has led to a greater understanding of the background around circularity in construction. This chapter will discuss the implications that a circular change can have for the current construction industry. Although the work in this PhD has answered many questions about the background to circular construction, the larger insights have also raised some new questions. Therefore, this section will discuss future opportunities for research in circular construction and set out some hypotheses for investigating some of the identified barriers to more circular construction.

6.3.1. More data on selective demolition and the environmental impact of preparing the reuse of components

Mapping demolition processes and derived environmental effects is generally poorly covered in research. With the changeover to selective demolition with subsequent reuse of the components, this opens up a large research area. This PhD thesis has mapped selective demolition processes on environmental impacts for a few building components, but similar studies should be carried out for all the most common building components that typically become available from demolitions. The results from selective demolition of the façade cladding showed that the selective demolition process had a greater environmental impact than conventional demolition because the operating times of machinery were longer. Today, construction regulation focuses on electrifying the construction phase to reduce CO_2 and noise, but the results for the selective demolition of façade cladding demonstrate the increased importance of also focusing on the electrification of machinery in connection with demolition processes. The results also showed that the dismantling techniques had a great impact on the loss of components that could not be reused and thereby also on the overall environmental savings that could be achieved. More research is therefore needed into the importance of demolition techniques in the demolition process to show how these techniques can be optimized so that the loss of components in selective demolition is reduced as much as possible and the environmental savings are maximized.

There are many different allocation methods for calculating the environmental impact of reuse. One such method that is often used in construction is to assume that, if reused components is 'burden free' because the entire environmental impact belongs to the first lifetime. However, the results of selective demolition with subsequent reuse of façade cladding clearly show that this is not the case because there are both environmental impacts associated with the selective demolition and, in addition, there may also be significant environmental impacts associated with the preparation for reuse. In the example of façade cladding, the CO_2 saving by recycling was 'only' around 46% compared to the conventional scenario and therefore far from burden-free. There is therefore a need for more studies of what preparation is required in order to make real reuse of various components where the function is maintained for as long as possible and to show how important the preparation is to the overall environmental savings that can be achieved by reusing components. With an increased focus on circularity in construction and new LCA requirements for construction, the need for correctly inputting data for reused components will grow.

6.3.2. The increased focus on circular construction in legislation

The development of legislation within sustainability in construction is today very much oriented towards new construction. For existing buildings, for several years the focus has been on energy savings and very little on the materials. With new sustainability classes in the building regulations and CO_2 limits, there is more focus on the environmental impact of the materials, but this is so far only the case for new buildings. The new CO_2 requirements have the potential to create a greater demand for reused and recycled materials and components and thereby support a growing market for circular material flows and processes. Because reuse is not considered waste, it is not covered by the legislation for construction waste. The lack of clear rules for reuse means that many companies are unsure about using reused components because it is not clear what responsibility is required of companies that sell components for reuse.

6.3.3. Collaborations and better detection of reusable components before demolition

One of the knowledge gaps that has been addressed in this PhD project is our lack of knowledge about materials in existing buildings. The material flow analyses showed that it is possible to access data on materials and components, but that the quality of the data is poor. By making a parametric material prediction model, it was possible to make better identifications of materials and components in existing buildings and also to generate a 3D model. Although it is possible to make better detection models for materials, it does not solve the biggest problem for the reuse, which is timing. When six times more square meters are constructed than demolished, only a limited amount of reusable and recyclable components and materials become available. There is therefore no guarantee that the components for a new building will be available on the market at the time they are to be inserted into the building. One solution is for contractors to collaborate with companies to deliver the specified amount of reused building components at a specified time. These companies can enter into an agreement with either the building’s owners or the demolition companies. Again, the time aspect becomes problematic because it is rare for the building’s owner to plan to demolish far into the future. There is generally a lack of research into the dynamics that influence demolition. In this project, several building-specific conditions such as age and use were uncovered in relation to demolition patterns. Future research can try to investigate where and when in the building's lifespan the decision to demolish is made. One hypothesis could be that demolitions rarely happen continuously under the same owner, but often happen in connection with sales and transfers of ownership. The research must therefore focus on how long there is from the decision to demolish to the actual execution of the demolition, and whether this period of time is long enough to be able to establish collaborations so that the materials are allocated to another building without their having to be stored for a long time after the demolition. In order for this to be successful, there must of course be a sustainable business case for using selective demolition with subsequent reuse, but it also requires that the building's owner stops describing the demolition itself as a necessary process that must be quickly completed and instead considers what were previously counted as waste products as new valuable resources.

6.3.4. A changing perception of the right amount of flexibility in relation to building design

During the development and testing of tools to measure flexibility, it became clear that many of the existing and tested tools only focus on the amount of flexibility, and not on its sustainability. When collaborating with the architectural companies in connection with development and testing, the goal was initially to achieve as much flexibility as possible in the design. However, there is no evidence of how the relationship between flexibility and sustainability develops in relation to different degrees of flexibility (see Figure 23). Overall, the reasoning around flexibility enabling the transformation of buildings and thereby preventing demolition and new construction is probably correct. If buildings have very low flexibility, the number of necessary changes can mean that many new materials have to be supplied. This in its turn can mean that the environmental impact and especially the economic price will be very high wherever there is a high probability of demolition. If the building is built with a very large degree of flexibility, this will mean that many building parts will have to be massively over-dimensioned. This can mean that the environmental impact of the construction will increase because more materials will be used and often also more energy in the building operation, since higher room dimensions will mean more outer wall with a heat loss.

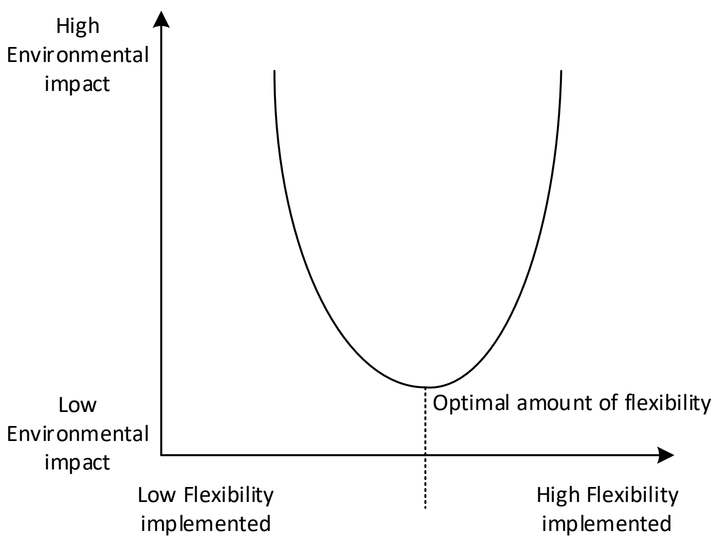

Figure 23. Hypothesis for the relationship between flexibility and sustainability.

When building flexibly, a higher upfront investment will be needed in relation to the environmental impact, which should hopefully result in a lower environmental impact in the long run if the flexibility activates circular measures later in the building's lifespan. Future research should focus on how much of the flexibility will be activated and how much will later lead to environmental savings. The hypothesis is that this point where flexibility leads to the most environmental savings (see Figure 23) is therefore the optimal amount of flexibility that will be achieved. The optimal amount of flexibility can vary for different buildings, depending on which parameters have an impact on whether and how a building will be transformed in the future. Before this optimal point can be identified, more research is needed into which flexibility parameters are most defining for different building types. One of the major challenges in planning and designing flexible solutions in new and existing buildings is that the long time horizon makes it very difficult to determine which type of flexibility will be needed in the future. This is also a problem that applies to many LCA calculations, which in construction often have time periods of over fifty years. One way to deal with this problem could be to research flexibility scenarios and thereby obtain an operating interval for the optimal amount of flexibility that can be used as a supporting decision-making tool in connection with planning and design processes in construction.

7. Main Conclusions

7.1. Data on existing buildings

In this thesis, a data mapping of registration requirements in Danish building legislation was used to identify publicly available data for existing buildings. The identified data was then tested in relation to its quality, availability and ability to provide information about the renovation potential and identification of materials. A total of four main databases were identified with publicly available data on existing buildings, as well as municipal semi-public databases containing waste data for demolished buildings.

Although there is a large amount of data available for existing buildings in Denmark, the testing of the data showed that there are still significant gaps in relation to its ability to inform and identify refurbishment potentials and circular potentials, and that the quality of the data is also a limitation. One of the major data gaps was data on materials in existing buildings, which is an important prerequisite in the quantification and identification of reusable and recyclable materials. An attempt was made to remedy the lack of data using extracted data on waste from demolished buildings coupled with classic material flow analyses, but the results showed that the quality of data on construction waste is currently too low, partly because there has previously been no focus on minimizing misregistrations in the reported data. An alternative parametric method for predicting materials was suggested such that, on the basis of typology studies, both a 3D model with building components and more precise material estimates could be generated. However, new Danish legal requirements for the registration and weighing of construction waste have the potential to improve the quality of input data for both classic material flow analyses and parametric models, thereby improving the possibilities for making precise material predictions and assessments of circular potentials.

7.2. Demolition trends and patterns

The data mapping showed that the Danish BBR register contains building-specific data such as construction year, use and floor areas for all buildings that have been demolished in Denmark. As buildings are deleted from the BBR when they are demolished, it was not possible to directly access data for all demolished buildings. By combining lists of the annually demolished buildings in all municipalities with historical BBR data from before the building was demolished, a combined dataset was created with data for over 120,000 demolished buildings. The combined dataset was subsequently used to map trends in demolition patterns and evaluate the Danish method for calculating the lifespans of existing buildings.

The main conclusions from the analyses of demolition data are that industrial buildings make up the vast majority of the square meters demolished and that housing only makes up about 20%. This can be linked to a decreasing need for industrial buildings and an increasing need for housing, which now make up about 80% of all newly built square meters. A trend was also identified in which newer buildings are demolished more often in Copenhagen, whereas older buildings are demolished more often in the rest of Denmark, even though the construction period for the existing building stock is relatively evenly distributed. Based on the data and the results, there are no clear indications of any large building-specific differences that could cause the variation in the age of the buildings being demolished in Copenhagen and nationally. This may indicate that the difference is caused by social or political conditions that should be further investigated.

With an alternative method of calculating the classic lifespan used in Denmark and the larger dataset on cases of demolition, it could be concluded that existing buildings potentially have a much longer lifespan than new buildings. Using the new method, an assessment was made that newer office buildings ‘only’ have an expected average lifespan of 37 years, which is significantly lower than the standard lifespan of 80 years that is used for offices in Denmark for profitability calculations, and the consideration period of 50 years that is used in LCA calculations. This can therefore have a very large impact on the building's overall environmental impact, and a more in-depth assessment of the lifespan of all building uses in Denmark should therefore be made on the basis of the dataset with the 120,000 demolished buildings.

7.3. Quantifying circular construction

Circularity as a concept has been used in construction for some years, but in practice it has been implemented to a very limited extent and has mainly focused on the recycling of construction waste. One of the biggest environmental benefits of recycling is that it reduces the need for new virgin materials, but with increasing greenhouse gas emissions and climate change, there has also been a focus on the greater implementation of high-value strategies for circularity, such as reuse of components and waste prevention (reduce) through refurbishment and adaptive reuse. In addition to the material savings, the big advantage of reuse and waste-prevention design strategies as refurbishment and adaptive reuse is that it requires less materials processing and handling than recycling and is therefore much less energy-intensive and saves greenhouse gas emissions. Because the focus has previously been on recycling, there is a lack of knowledge about the processes and environmental impacts or benefits of reuse or of how the flexibility of waste-prevention design strategies can be quantified.

Through a case study of a selective demolition, data was obtained on selective demolition processes. These data, together with data from conventional demolition processes, were used to make a comparative LCA study of the environmental impact of selective demolition and the environmental benefits of the subsequent reuse of steel façade cladding against the conventional demolition with subsequent recycling of the steel and new production of virgin façade cladding. The study showed that the environmental impact of the selective demolition process was larger than in the corresponding conventional demolition process, but also that the environmental benefits of reuse meant that the selective reuse scenario had a lower environmental impact than the conventional scenario in all the eighteen assessed environmental impact categories. The results showed, however, that the total environmental savings of greenhouse gas emissions in relation to reuse was 'only' 40-45% in relation to the conventional scenario and therefore far lower than the 100% saving that is sometimes assumed by the burden-free method when reuse products are used in LCA calculations. This therefore shows the importance of doing more LCA studies of selective demolition and reuse in order to provide correct input data for future building LCA calculations.

One of the circular strategies for existing buildings that have the lowest environmental impact is to change as few building elements as possible. These waste-reducing strategies for buildings are realized by avoiding both partial and total demolitions, often by maintaining or optimizing the building through refurbishment strategies or adapting the building's functions through adaptive reuse. Common to both strategies is the fact that the vast majority of the building does not become waste, which results in both large material and environmental savings. One of the challenges today is that it is difficult to calculate how flexible existing buildings are in adapting to changing needs and functions. In this study, an investigation was made of the methods and indicators that exist to measure flexibility and the capabilities of buildings. The most commonly recognized indicators from previous research projects were collected in a tool. Using criteria from other building assessment tools, a transformation potential tool was created to quantify the flexibility of existing buildings. In order to make the tool operational as a method of quantification and visualization that can provide information about the building's existing flexibility and the consequences of design decisions on that flexibility, knowledge is still lacking about which building-specific conditions are the most defining for whether a building can be transformed. At the same time, the tool is also very data-intensive, and the data-mapping in part 1 of this thesis showed that, although there is a lot of data on existing buildings in Denmark, there is a lack of data on the building's structural building parts and on the interior layout of buildings. Another general prerequisite for being able to quantify flexibility in both existing and new buildings is that there is a lack of knowledge and research into what is the optimal realistic amount of flexibility. Designing for flexibility will often mean a greater upfront price and environmental impact in the construction because the building's parts must be over-dimensioned and possibly made multi-functional. If the flexibility is not later realized or activated, then the potential future environmental savings are not redeemed and the flexible building has had a greater environmental impact overall over its lifespan. In order to be able to support and inform architectural design processes with reference to the most circular and flexible strategies, there is therefore a need for a research study of possible scenarios for a circular future and which types of flexibility have the greatest potential to be realized in the circular construction of the future.

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Appended Papers

Journal Paper 1

JP1: Using digitized public accessible building data to assess the renovation potential of existing building stock in a sustainable urban perspective.

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Using digitized public accessible building data to assess the renovation potential of existing building stock in a sustainable urban perspective

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ABSTRACT

Being able to assess potentials and obstacles regarding different optimization scenarios for an old building is essential. However, the data needed to provide this information should be operational and suitable for the early design and planning phases of rebuilding or renovation. The purpose of this study is to investigate the possibilities of using information from public registers and databases on existing buildings as possible input data to inform designers and other stakeholders about the renovation potential of existing buildings in urban developments. This includes evaluating sustainability indicators for indoor climate, energy savings, flexibility, affordability, materials composition, recycling opportunities, etc. Denmark is a frontrunner in digitalizing building data and making them publicly accessible. The results of a mapping of three public building registers and databases show that they – although they were initially established for purposes of taxation, preservation, and energy savings can be put to new use in a circularity perspective. However, even though Denmark is far in the digitalization of building data, the analysis also shows that there are data gaps, outdated data, and errors in registrations that still need to be addressed. Therefore, this article lists recommendations for developing national or regional digital building data registers to support better decisions about renovation and urban development.

1. Introduction

The building sector is a significant contributor of global impacts on the environment, such as global warming due to emissions of greenhouse gases. Indeed, the building and construction sector was responsible for nearly 40% of all energy-related CO_2 emissions in 2018 (UNEP, 2019). Furthermore, construction and demolition waste are responsible for 34% of the urban waste produced by OECD countries (Wilson et al., 2015).

However, the demand for new buildings will continue to increase, as will urbanization. In 2018, 55% of the world's population was living in urban areas, which is estimated to rise to about 68% by 2050 (United Nations, 2018). Urbanization creates a demand for more dwellings, resulting in increased demolition and new construction (Huuhka & Lahdensivu, 2016), increasing the generation of construction and demolition waste and the demand for new materials. One of the remedies to this dilemma is to optimize the existing building stock to improve energy efficiency and ensure better health and well-being of occupants (Woetzel, Ram, Mischke, Garemo, & Sankhe, 2014).

A Danish case study has shown that the environmental impact of renovating a building can be reduced to 40% of the environmental impacts associated with the construction of a new similar size building (Rasmussen & Birgisdóttir, 2015). An analysis of sixteen buildings carried out by the engineering company Rambøll showed an advantage in choosing renovation rather than demolition and replacement regarding CO_2 emissions and costs in all sixteen cases (Sørensen & Mattson, 2020). In order to provide accurate information about the potential of renovation as opposed to demolition and replacement, assessments of options for improvements are required during the early planning stages (Geraedts & Van der Voordt, 2003). Indicators can be used to indicate the potential for renovation and improvements (Vilutiene & Ignatavičius, 2018), and the lifespan of buildings can be extended by assessing the current performance of a building and visualizing renovation plans with the use of indicators (Cortiços, 2019). There is currently a lack of knowledge and established tools when making sustainability design decisions regarding existing buildings (Noor, Syed, Ariffin, & Ismail, 2014), where the data are of limited availability or expensive to collect. (Monzón & López-Mesa, 2018) have shown that applying data from energy labels and noise maps on building and urban level, into key performance indicators for energy consumption, noise, and accessibility

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makes it possible to detect buildings in bad condition. In relation to developing methods for assessing sustainability issues on an urban or district level it is crucial to apply universal practices that are transferable to other situations and aim for what is standardized in regards to indicators. However, as locations are different, it is still important that there is some flexibility in adapting the method, tool, or criteria of the indicators to the specific urban system (Hély &Antoni, 2019; Kleemann, Lederer, Aschenbrenner, Rechberger, & Fellner, 2016; Pelorosso, 2020).

A potential way of handling the data challenge in buildings is to use automatization and Building Information Modelling (BIM) (Barbosa, Pauwels, Ferreira, & Mateus, 2016). In December 2018, the Danish government launched a strategy for achieving a circular economy. One of its initiatives was to support more digitalization and use of data to create information about materials in products and buildings, where they can be found, and whether they contain problematic substances (Ministry of Environment and Food, 2018). However, BIM and automatization are primarily used in larger new construction projects and only rarely used for the existing housing mass, which, due to the low number of BIM models for the existing buildings, can be costly and time-consuming to establish (Hossain & Yeoh, 2018). Several studies have shown that it is possible to make analyses of possible energy retrofit interventions in buildings on an urban scale through public data (Caputo & Pasetti, 2017; Ferrando, Causone, Hong, & Chen, 2020; Pistore, Pernigotto, Cappelletti, Gasparella, & Romagnoni, 2019; Pittam, O'Sullivan, & O'Sullivan, 2014), or predict future renovation cycles through public data (Sandberg, Sartori, & Brattebø, 2014). However, these studies have identified limited data availability and fluctuating data quality as a barrier, and therefore there was often a need for physical collection of data through inspections. Using data from public data registers in Sweden, (Österbring, Camarasa, Nägeli, Thuvander, & Wallbaum, 2019) has shown that it is possible to make a bottom-up model for energy use reductions for house portfolios in the City of Gothenburg. Using public data, it is also possible to extend the method to other cities in Sweden or countries with the same data structure.

Urban development is also a focus area for the European Union that have launched The Urban Agenda program in May 2016 through the Pact of Amsterdam (European Commission, 2016) with the increased focus on promoting coordination and cooperation on urban development between the member states. The program has, together with partnerships, established fourteen action plans of different urban subjects such as housing (Urban Agenda for the EU, 2018b), digital transition (Urban Agenda for the EU, 2018a), circular economy (Urban Agenda for the EU, 2018c), cultural heritage (Urban Agenda for the EU, 2018d) or urban poverty (Urban Agenda for the EU, 2018e). One of the newest initiatives in the EU on renovation and urban development is The New European Bauhaus launched in January 2021 (European Union, 2021). The initiative aims is to kick start a new European renovation wave focusing on integrating circularity, aesthetics, and affordability as an action under The large European Green Deal plan from 2019 (European Commission, 2019).

An evaluation of European data availability in publicly available digital registers concerning the built environment in Finland, Copenhagen, Hamburg, and London showed that Danish and Finnish public registers were the most digitalized and contained the most building-level data due to their legislation on building registration (Cartwright et al., 2020). Our hypothesis is that public building registers can provide easily accessible and cheap data needed to make sound planning decisions during the early design phase in order to assess the potential for the optimization of existing buildings. This article aims to examine Danish building registers to determine whether sufficient data can be obtained for a set of building indicators. This was done by investigating the following:

1 Selection of indicators for mapping based on research studies of indicators relevant in evaluating renovation potentials in the planning and design phases of existing buildings.
2 Investigate what standardized data requirements the different indicators selected in Step 1 could be based on.
3 Review Danish building and waste legislation to establish the data registration requirements for buildings that meet the data needs that were identified in Step 2.
4 Examine data availability for two case studies of urban areas.

2. Methods

2.1. Indicator categories selection

In connection with the development of construction projects, sustainability indicators are an effective tool for measuring environmental, social, and economic sustainability performance (Tupenaite, Lill, Geipele, & Naimaviciene, 2017). Indicators can be used in the early planning phases as a strategy tool, in the design phases as an optimization tool, during construction as a monitoring tool, or as a tool evaluating the sustainability performance of the finished building, as is done in sustainability certification schemes such as the German DGNB system (Møller, Rhodes, & Larsen, 2018). This article will focus on indicators that can be used to evaluate the current sustainability performances of existing buildings to inform decisions in the planning phase of urban renewal. A vast number of indicators for measuring the performance of existing buildings have already been established (Kylili, Fokaides, & Lopez Jimenez, 2016). The selection of indicators for the data mapping was based on studies that have used different methods to assess the importance of key indicators and ranked the indicators hierarchically, as showed in Table 1. The ranking in the studies is based on (i) literature study of indicators widely used in the Baltic regions (Tupenaite et al., 2017) (ii) stakeholder perceptions and values of indicators categories in the different building phases (Alwaer & Clements-Croome, 2010).

In these studies in Table 1, there is consensus concerning the importance of a group of indicators. This applies to energy, materials, waste, affordability, and indoor environmental quality. However, there are also differences; were the study from (Alwaer & Clements-Croome, 2010) identified several architectural indicators as important (Tupenaite et al., 2017) has assessed them as having a minimal weighting. (Alwaer & Clements-Croome, 2010) has not included urban indicators, which are, considered important around neighborhood/community considerations by Tupenaite et al. (2017).

In the mapping, two indicator categories where there is a consensus were selected from each of the environmental, social, and economic impact categories. There was a consensus between the two studies that energy and materials/waste were significant in the environmental

Table 1
Hierarchical structure of sustainability indicators categories in the two studies.

	Alwaer & Clements-Croome (2010)	Tupenaite et al. (2017)
TOP THREE ENVIRONMENTAL INDICATORS CATEGORIES		
	Energy and renewable energy	Energy and atmosphere considerations
	Material used, waste and durability	Materials and waste management
	Functionality, usability & aesthetic aspects	Indoor environmental quality
TOP THREE SOCIAL INDICATORS CATEGORIES		
	Architectural considerations	Accessibilities
	Indoor environmental quality	Neighborhood/community considerations
	Daylighting and illumination	- (Only two social indicator groups in the study)
TOP THREE ECONOMIC INDICATORS CATEGORIES		
	Economic performance & affordability	Housing affordability
	Flexibility & adaptability (FA)	Added value
	Management, intelligence and controllability	Satisfaction of demand

category, so they were selected for the mapping. There was a consensus that indoor environmental quality was an essential indicator, even though (Tupenaite et al., 2017) described is as belonging to the environmental category. There is no overlap on other indicators in the social categories. Architectural Considerations was selected for the mapping based on the observation that this indicator can have significant impact on what is allowed to change on existing buildings regarding preservation restrictions. For the economic category, there is an agreement between the studies that affordability is an important indicator. In addition it is assumed that flexibility/adaptability is equivalent to the added value indicator.

2.2. Selection of indicators in categories and data requirements

There is no standardized system for indicators, which can also be seen in Table 1, where indicator groups have different names. There are also disagreements about whether some indicators should be classified as environmental or social, as was the case with Indoor Environmental Quality. To find data for indicators that are as standardized as possible, a study was made of how the selected indicators from 2.1 corresponded to the requirements in existing standards and in well-established building certification systems (the German DGNB system was chosen as reference). Furthermore, a literature study of consensus concerning calculation methods and data requirements for the selected indicators was performed. The results of both analyses (standards and literature study of calculation methods) are shown in Table 2, related to the chosen indicators. The indicators in Table 2 that form the foundation for the data mapping are thus selected because there is a consensus of their importance for this particular research question (stakeholder interviews etc. performed by Vilutiene et al. (2018), they are included in standards, and well-established sustainability certification systems and there exists well-defined calculations methods and data requirements.

The purpose of this study is to examine data availability and not go in-depth with the calculation of all different types of indicators. All identified data from the mapping is stated in the supplementary data to this article for information on available data that can be used in other alternative indicators.

2.3. Policy and legislation backdrop for data-mapping

To find public building data and identify requirements for registering of different building conditions relevant to the six selected indicators, a mapping of Danish building regulations was carried out. The primary legislation affecting building energy, preservation, waste, taxation, and building regulations in bold in Fig. 1. The mapping was based on these five pieces of legislation and any associated supplementary legislation.

2.4. Case study

To investigate the data availability and potential for public registers to provide the data in Table 2, a case study was conducted of two residential areas near Copenhagen: Tingbjerg, built in the 1960s, and Tåstrupgård, built in the 1970s. They were chosen because they date from two different periods, though they are both of high technical standard and are located in areas subject to major urban renewal. The case study was conducted by searching for information in the identified databases on the selected indicator's data requirements for each location. The addresses used for searching information in the databases were "Gavlhusvej 19, 2700 Brønshøj" for the Tingbjerg area and "Taastrupgårdsvej 11, 2630 Taastrup" for the Tåstrupgård area.

3. Results

3.1. Legislation registration requirements in registers

The study showed that the recorded data for the chosen indicators were available in three publicly available building registers.

Table 2
Mapped indicators from the selected categories and their individual data requirements.

CATEGORY	INDICATORS	REFERENCE TO ASSESSMENT OF INDICATOR
1) ENERGY & RENEWABLE ENERGY		
	Energy consumption [kWh/m2]	Vilutiene et al. (2018)
	Existent energy class of building [Letter]	Vilutiene & Ignatavičius, 2018
2) MATERIALS AND WASTE MANAGEMENT		
	Components for re-use [kg]	EN 15,978 European Committee for Standardization (2011)
	Materials for recycling [kg]	EN 15,978 European Committee for Standardization (2011)
	Materials for energy recovery [kg]	EN 15,978 European Committee for Standardization (2011)
	Hazardous waste disposal [kg]	EN 15,978 European Committee for Standardization (2011)
	Non-hazardous waste disposal [kg]	EN 15,978 European Committee for Standardization (2011)
3) ARCHITECTURAL CONSIDERATIONS		
	Architectural qualities or listing status [Number]	InterSAVE Tønnesen (1995)
4) INDOOR ENVIRONMENTAL QUALITY		
	Concentration of substances [number of harmful substances]	EN 16,309 European Committee for Standardization 2014
	CO2 concentration [ppm CO_2]	EN 16,309 European Committee for Standardization 2014
	Ventilation rate [l/s/m3]	EN 16,309 European Committee for Standardization 2014
	Radiation from radio [Bq/m3]	EN 16,309 European Committee for Standardization 2014
5) FLEXIBILITY & ADAPTABILITY		
	Space efficiency [usable floor area (UA) / gross floor area]	DGNB ECO2.1 DGNB GmbH 2020
	Ceiling height [meters]	DGNB ECO2.1 DGNB GmbH 2020
	Building depth [meters]	DGNB ECO2.1 DGNB GmbH 2020
	Vertical access [number of access cores]	DGNB ECO2.1 DGNB GmbH 2020
	Structure [Are internal partitions load-bearing]	DGNB ECO2.1 DGNB GmbH 2020
6) AFFORDABILITY		
	House price to income/earnings ratio [house price and average income]	Meen (2018)

3.1.1. Main Danish building and dwelling register (BBR)

The first register identified through the mapping was the Danish Building and Dwelling Register (BBR), which was identified in LBK no. 797 of 06/08/2019 §1:

"*The Minister of Taxation must establish and operate a nationwide register with information on building and housing specifications as well as technical facilities. Each municipality maintains this register in accordance with rules established by the Minister of Taxation. The Building and Housing Register (BBR) aims to 1) contain basic data about building and housing conditions as well as technical facilities, etc., 2) contain a unique registration of all buildings, residential and commercial units as well as the technical facilities and technical units entered in the register 3) make data available to public authorities, concessionaires, individuals and companies.*" (Danish Ministry of Taxation, 2019).

Information in the BBR relates to the property-, building- and unit-

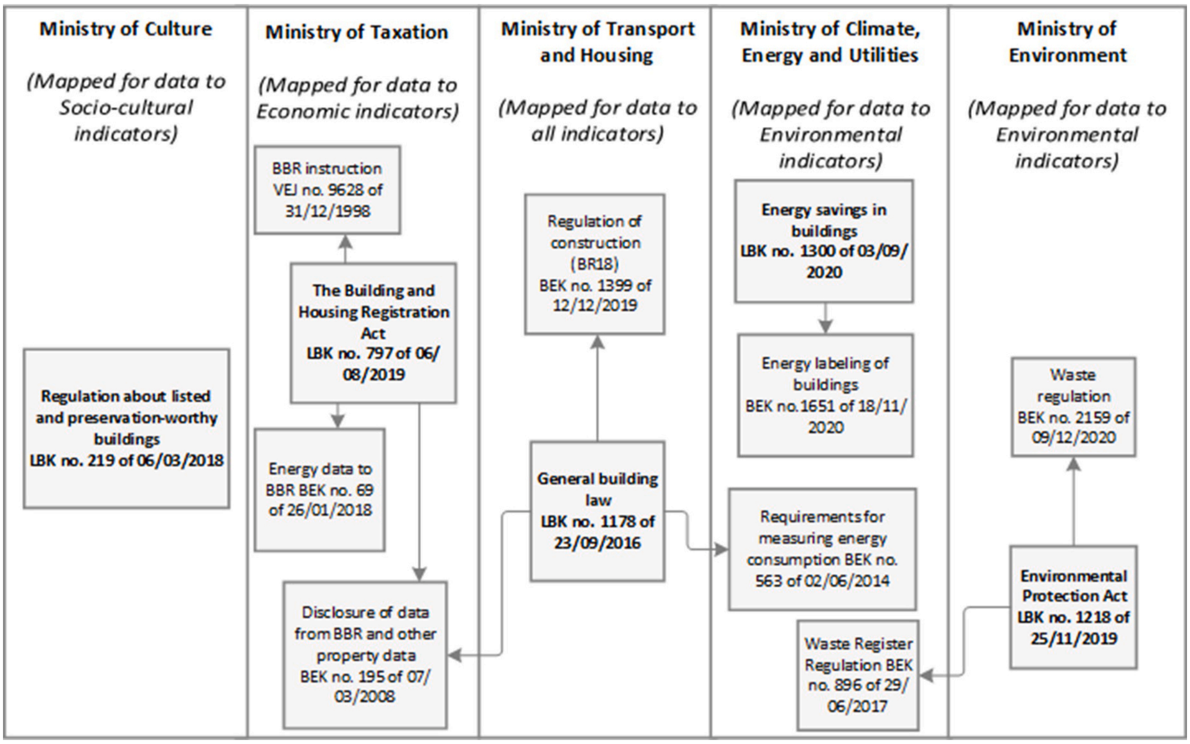

Fig. 1. The selected legislation is shown in bold. The remaining legislation is supplementary legislation that was identified in connection with the review.

levels, e.g. apartments in the latter case. A BBR registration of property may contain information on several buildings. Registration structure and content in the BBR is described in the supplemental instruction to the BBR Law, VEJ no. 9628 of 31/12/1998 (Danish Ministry of Taxation, 1998). Data in the BBR are publicly available and can be accessed through digital public platforms as OIS.dk (Danish Ministry of Taxation, 1998).

3.1.2. *Register containing building preservation status*

The second building register was identified in the regulation on listed and preservation-worthy building LBK no. 219 of 06/03/2018 (Danish Ministry of Culture, 2018) where it is stated in § 20 that the Minister of Culture must maintain a publicly available list of protected areas under the law. The legislation does not describe which database and what this database must contain. However this can be found in a supplementary amendment to the law where it is mentioned in a note to §20 that:

"The requirement has been met over the years by maintaining an updated list of all listed buildings in book form that has been published on a regular basis. In 2006, the database of listed and preservation-*worthy buildings, (FBB),* (www.kulturarv.dk/fbb), *was published, and an all-time updated register of the listed buildings and works has been created."* (Ministry of Culture, 2009)

Therefore, the Ministry for Culture is responsible for the FBB ("Fredede og Bevaringsværdige Bygninger" directly translated to Listed and Preservation-worthy Buildings) register and database. The preservation status in the register is evaluated using the so-called Survey of Architectural Values in the Environment method, most commonly referred to as the SAVE method. Development of the SAVE method started in 1987, it having been widely used in Denmark since 1991 (Kulturarvsstyrelsen, 2011). The FBB register is managed by the Agency for Culture and Palaces, a department under the Ministry of Culture. The FBB database contains about 9000 listed and 355,000 SAVE-evaluated buildings (Ministry of Culture Denmark, 2021). The FBB database is publicly and digitally accessible (Ministry of Culture Denmark, 2021).

3.1.3. *Register containing building energy data*

The third building register was identified in regulation LBK no. 1300 of 03/09/2020 (Danish Ministry of Climate Energy and Utilities, 2020a), which states in §25 that the Ministry for Climate, Energy and Utilities must establish and manage a register of the energy labelling of buildings and the inspection of technical installations. An additional Notice BEK no. 1651 of 18/11/2020 (Danish Ministry of Climate Energy and Utilities, 2020b) regulates the overall rules for the energy labelling, while the technical registration content of the energy labelling is regulated by Notice BEK no. 792 of 07/08/2019 (Danish Ministry of Climate Energy and Utilities, 2019). The energy labelling of buildings is mandatory for new buildings in order to demonstrate that the building complies with the Danish building regulations BEK no. 1399 of 12/12/2019 (Danish Ministry of Transport and Housing, 2019). Furthermore, it is mandatory for a building to be able to produce a valid Energy Performance Certificate when it is sold or rented. Energy Performance Certificates are valid for ten years. In 2018, 560,000 Danish buildings had a valid energy label (Danish Energy Agency, 2019b). The Energy Performance Certificates consist of a report with an energy label based on a generic energy calculation. Both the report and the energy calculation file with all the building registrations are accessible in the energy label database and can be downloaded via the web service *EMOData* (Danish Energy Agency, 2019a).

3.1.4. *Register containing construction waste data*

In addition, a database was also identified with information on construction waste, which, however, is not publicly available. According to the Waste Regulatory Law BEK no. 2159 of 09/12/2020 (Danish Ministry of Environment, 2020) §70, companies and private individuals are required to notify the municipality about building waste expected to be produced by demolition or renovation fourteen days in advance. The minimum information that must be specified in the notification are the building address, the year of construction or renovation, the predefined PCB (Polychlorinated biphenyl) screening scheme and the expected waste amounts (in tons) and expected waste-handling procedures. There are no regulations providing for a single main Danish database: instead, the individual municipality has to provide a digital system to record these notifications. The data is owned by the individual municipalities and is not publicly available.

3.2. Data availability

The registration structure of the BBR is clearly described in VEJ no. 9628 of 31/12/1998 (Danish Ministry of Taxation, 1998), where there is information on which standard texts can be chosen in connection with the registration. Similarly, the energy label in BEK no. 792 of 07/08/2019 (Danish Ministry of Climate Energy and Utilities, 2019) had a clear description of which building elements are covered by the registration. No description of FBB database registration requirements was found. As shown in Table 3, some indicators could have information from several of the databases concerning the same topic, such as energy consumption. However, there was a difference in how the registers addressed the same topic. For instance, the energy label contains a calculation of the energy consumption, while in the BBR, there is a requirement to register the actual energy consumption.

The registration of actual energy consumption is the responsibility of the company that supplies energy to the building. According to the Building and Housing Registration Act §5 (Danish Ministry of Taxation, 2019), actual energy consumption is only available to the building owner. It is therefore not publicly available from the database.

No requirements were found in the legislation for registration concerning the CO_2 concentration or radiation from radon in the existing buildings, However, a theoretical CO_2 concentration may be calculated based on the ventilation rate (Persily et al., 2017) stated in the energy label. Registration of the material composition of existing buildings to enable assessments of amounts of recycling or the energy recovery potential of materials was only identified in connection with the notification of demolition waste to the municipality and was not publicly available. This information is only registered for materials that have already been removed from the building. Therefore there is no data on the materials that are located in the existing buildings. The type of exterior wall and roofing material is listed in the BBR, but no quantities or expected handling are registered. Concerning affordability, the public property assessment is available through OIS.dk, where data on the publicly assessed housing price are retrieved from SVUR ("Statens Salgs- og Vurderingsregister" translated to The State Sales and Valuation Register) and are calculated partly on data from BBR.

3.3. Case study of buildings in Tingbjerg and Tåstrupgård

The case study of the building level concerning data availability for the indicators in the two areas showed that information in the BBR was easily accessible for both locations. The majority of the buildings in both locations were in the same BBR register since they were located on the same cadastre. In the Tingbjerg case, no registration could be found indicating whether the load-bearing structure consists of a concrete frame or records the presence of asbestos. In the Tåstrupgård case, asbestos was registered in roof-cladding. The BBR also included the year of construction for both cases and, in addition, stated that the building in Tåstrupgård had been renovated or extended in 1989.

The energy label for Tingbjerg, ID 311058902, turned out to include the same buildings covered by the registration in the BBR. However, obtaining technical registration data for individual buildings was possible by downloading the XML calculation file in the energy label database. In the energy label, the exterior parts of the building were listed with descriptions, areas, and thermal properties. It was thus possible to determine that the case-study building in Tingbjerg had an uninsulated 36 cm solid exterior wall of brick with a total area of 1144 m^2. For windows and doors, the type, areas, thermal properties, and area of glass were registered. The buildings in the energy label used BBR identification codes, making it possible to search for information about a building via the building ID in the BBR register. Searching the energy label database for the address in the Tåstrupgård case showed that no energy label was registered at the address. It was therefore not possible to retrieve information from the energy label for that case study.

Table 3
Results of data availability in the three identified public building registers.

DATA REQUIREMENTS	DATABASE	DATA AVAILABILITY
ENERGY & RENEWABLE ENERGY		
Energy consumption (kWh/m2)	Energy label & BBR	Calculated energy use from the energy label. Actual energy consumption in BBR.
Existent energy class of building [Energy label]	Energy label	Current energy class (label) as well as future energy classes if all profitable energy improvements are carried out
MATERIALS AND WASTE MANAGEMENT		
Components for re-use [kg]	No registration	–
Materials for recycling [kg]	Municipal waste data	Is registered in tons for demolished buildings. Not publicly available.
Materials for energy recovery [kg]	Municipal waste data	Is registered in tons for demolished buildings. Not publicly available.
Hazardous waste disposal [kg]	Municipal waste data	Is registered in tons for demolished buildings. Not publicly available.
Non-hazardous waste disposal [kg]	Municipal waste data	Is registered in tons for demolished buildings. Not publicly available.
ARCHITECTURAL CONSIDERATIONS		
Architectural qualities or listing status	FBB database	Preservation status rated on a scale from 1–9
INDOOR ENVIRONMENTAL QUALITY		
Concentration of substances [list of harmful substances]	BBR	Can be assessed based on construction year from BBR. Asbestos in roof and walls are registered in BBR.
CO2 concentration [PPM]	No registration	–
Ventilation rate [l/s/m3]	Energy label	Ventilation type and rates in l/s/m2
Radiation from radon [Bq/m3]	No registration	–
FLEXIBILITY & ADAPTABILITY		
Space efficiency [usable floor area (UA) / gross floor area]	BBR	Gross floor area and housing/industrial floor areas are listed in BBR
Ceiling height [meters]	No registration	–
Building depth [meters]	No registration	–
Vertical access [number of access cores]	No registration	–
Structure [Are internal partitions load-bearing]	BBR	Main load-bearing construction system if the building has reinforced concrete frames
AFFORDABILITY		
House price to income/earnings ratio [house price and average income]	SVUR	The publicly assessed property price are partly based on BBR data and can be found through OIS.dk

The FBB register showed that the majority of the buildings in Tingbjerg were covered by the same registration, and therefore information about individual buildings could not be accessed. However, the notice also stated that the buildings had a high preservation status and were rated as value 2, the second-highest preservation status. None of the buildings in the Tåstrupgård case had a preservation status or was listed, and therefore none of them were registered in the FBB database.

All buildings in the two case areas are social housing, and therefore it was not possible to calculate an affordability indicator based on the value of the buildings since all apartments are tenants and not privately owned. In addition, the principle of social housing is also that they must be affordable.

4. Discussion

4.1. Data availability

The results indicate that, since no requirements to register amounts of materials or recycling possibilities were found in any of the databases, there is insufficient information to estimate the total material composition of the buildings. However, the Tingbjerg case study showed that material information for some of the larger materials fractions, such as the outer walls, roof, and windows, could be located if material identification of the envelope from BBR was connected with the registered areas for the envelope parts of the Energy Label. There is also information in the database relating to the notification of construction waste, which can support studies estimating the material composition of buildings. No such studies have been performed at present, and therefore it is not possible to use these data for the buildings in the case study. Registrations of construction year, floor areas, and building use in the BBR could provide data to establish and identify building typologies in Denmark. If this is coupled with waste data from the demolition waste register, then it could help provide information about the potential for urban mining and renovation. Assessments of the reuse and recycling potential of the materials from the building are based on the materials identified for urban mining. They will therefore be limited by the lack of information on the detailed material composition of the building. The information about hazardous materials in the BBR mainly focused on asbestos. Still, registrations of PCB are also relevant for the recovery of materials and components and the need for indoor improvements to air quality when making renovations. However, no registration requirements were found concerning the presence or concentrations of PCB in the building materials. PCB was mainly used in buildings in Denmark from 1950 to 1977 (Olsen & Olsen, 2015), so the year of construction registered in the BBR could be used to estimate the risk of PCB and other hazardous substances in the building materials.

The Tingbjerg case showed that the energy label could provide detailed technical information about energy systems and be used as input data to calculate the energy saved from acquiring components. In addition, the calculated energy consumption could be used to identify target buildings for energy optimization. The FBB database could provide information about the condition of a building, its preservation status, and its place in its urban environment. This can be used to assess the importance of preserving the building where buildings with lower scores could instead be more suitable for demolition. However, the case study showed that the FBB registration for Tingbjerg was elevated to become a single registration for the whole area, limiting its usability concerning the potential for urban mining and renovation when there are several very different buildings (typology) in the area. The registration structure in the BBR made it challenging to assess whether a lack of registration means that registered data requirements do not exist for the building in question or whether its registration is missing from the database. This problem occurs for asbestos or load-bearing concrete frames in the BBR, which are only described in this register if they are present in the building. Furthermore, registration in the FBB and the registration of energy labeling were not available in the Tåstrupgård case, even though this is a legal requirement for buildings of this size if they are rented out (Danish Ministry of Climate, 2019).

4.2. Recommendations for use of register data to support renovation decisions

When using building register data, the big dilemma is the relevance and accuracy of the data versus their availability. The SAVE evaluation from the FBB database can, in some cases, be around twenty to thirty years old. In the meantime, many building changes may have been introduced, which means that the preservation status or the condition of the building registered in the database does not correspond to the present reality. Similarly, the energy labels that can be accessed in the energy label register may be up to ten years old. In addition, the purpose of the energy label is also to provide information about the potential for energy improvements, so there is a high probability that the new owner of a building will implement several of these potentials, which in reality makes the energy label out of date and thus unsuited for basing decisions.

The use of register data should ideally be easily accessible and time-saving while still providing robust indicator results on which to base decisions during the early planning stages. However, as the case studies show, building register data have several limitations, and it is crucial to be aware of them. Thus, when using register data, it is essential first to clarify the acceptable margin of error in the indicator results concerning to the transformation or renovation strategies. As noted earlier, this margin of error may be due to the low quality of the available data or too large data gaps in the registers, as was the case for the data on Tåstrupgaard. If the error is deemed too large, then building register data should be reconsidered. It may be necessary to make more extensive onsite inspections instead of making decisions based on low-quality register data.

4.3. Recommendations for the development of national or regional building data registers

The establishment of centralized Danish building registers has taken place over a long period, starting with the BBR in 1976 (Danish Ministry of Taxation, 1976). Historically, data have mainly been collected manually, and energy labels and SAVE evaluations are, for instance, still lacking for a large part of the existing building stock. When establishing registers or expanding established registers, it can be advantageous to gather all the information in the same registers so that the availability becomes more significant, making it possible to cross-validate the data from the different registers to increase their quality. In this way, energy label data could help determine whether the information in the BBR register is correct and vice versa. Most energy labels are also made by physical inspections and could potentially support the energy consultant in also examining whether the building registrations in the other registers are correct or gather new registrations. There could also be advantages in implementing more digitalization when establishing new registers and investigating opportunities to auto-generate data for buildings. Waste data from the register of notifications to the municipality can potentially be used to assess the material composition and recycling potential of existing buildings by examining the typical material composition of demolished buildings from the register, data which, however, is not publicly available at present. A building can experience many changes over its lifetime in connection with renovations or ongoing maintenance, so there can often be discrepancies between the data in the registers and the actual conditions in the building. There is a lack of more knowledge and research on how much uncertainty can be allowed to uncover potentials for improvements in early planning and how much error margin is acceptable for register data. Studies of data quality in the Danish energy labels have shown significant errors in the registrations data, which would mean that 23% of the energy labels should have a different label value (The Danish Energy Agency, 2020), which is otherwise data obtained via physical inspections and therefore should be of high quality. It may, therefore, also be beneficial for the establishment of future registers to investigate how good quality digital auto-generative methods can deliver data and whether, with new technology, it is possible to provide much larger amounts of data to the same quality as data obtained by physical inspection. The introduction of new circular initiatives such as building and material passports will, in the future, also place more focus on the structuring and accessibility of data, clearly demonstrating the need to collect data centrally. Whether if new registers are established, or existing registers are expanded to provide data to gaps, there are some critical points to consider:

- Data can be expensive to obtain, so it is essential to clarify for what purpose the register is established so that the data collection and the later data use provide the most value. The data for indicators in this study could be a starting point for establishing data collection on energy, materials, architectural qualities, indoor environmental quality, flexibility, and affordability.
- Clarify how much data can be created with auto-generative methods such as satellite data or further development of existing non-centralized data, and how much uncertainty can be allowed concerning the data quality.
- If there is a need for greater data accuracy or if there are critical data gaps that cannot be met with auto-generated methods, the extent of audit data created with physical inspections must be assessed. However, there is an expensive method of obtaining data and can be costly to maintain.
- Finally, it is important to establish standardized data collection and registers so that data is collected and structured similarly so that analysis methods or indicators do not have to be adapted for each building case and can be used as a comparison between different projects or in larger urban areas.

5. Conclusions

The purpose of this study has been to investigate whether public building registers can provide easily accessible and cheap data for indicators to support assessments of the optimization potential of existing buildings in the early planning and design phases of urban development. Using a selection of eighteen sustainability indicators concerning their social, environmental, and economic performance and their data requirements, it was possible to review Danish construction and waste legislation and identify relevant registration requirements for building data in the legislation. This identified three public building registers for general building registrations, energy, and preservation, respectively. In addition, a review of the Danish waste legislation also identified the requirements for the registration of construction waste amount and expected recycling opportunities in connection with demolition and renovation. This registered waste data turned out not to be publicly available. However, it has the potential to support analyses of the material composition of building typologies, which can then be used to assess the urban mining and reuse potential of existing buildings. This is especially important because our review of the legislation showed no data on the material quantities of existing buildings in the three publicly available registers. A case study of two urban areas in Copenhagen showed that, in cases where all the registered data were available for a location, there was still not enough data to meet all the data requirements for the eighteen indicators. In addition, the case study also showed a lack of data in one of the case areas, which, according to the legislation, should be available. Furthermore, this article has provided an overview of the potential for using publicly available data, as a cheap and timesaving data source. However, by further developing registers and improving digital methods of validating and improving the quality of the register data, it should be possible to expand the potential for using public data as a screening tool in planning and assessing the potential for sustainable renovation and circular design strategies in early planning and urban development. The main question that this article tried to answer was whether public building registers could provide the easily accessible and cheap data needed to make sound planning decisions during the early design phase. The study showed that this is only partially possible as data for many of the selected indicators are still missing. Therefore, the study has also tried to develop suggestions for how data quality can be improved and how other countries can set up similar registers and learn from the experiences that can be gained from a Danish case. The recommendations from this study concerning the establishment of registers with building data i) select a clear purpose for the collection and utilization of data ii) create standardized guidelines for data collection and setup of registers iii) identify needs between quantity and quality of data and whether it is possible to obtain cheap data through data auto-generative methods instead of data acquisition by expensive physical inspections.

Declaration of Competing Interest

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

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Supplementary materials

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Journal Paper 2

JP2: Parametric Stock Flow Modelling of Historical Building Typologies.

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Article

Parametric Stock Flow Modelling of Historical Building Typologies

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Abstract: While the construction sector is a major consumer of new raw materials, it also contributes largely to waste generation. Therefore, improved estimates of demolition waste and the identification of components and materials for reuse or recycling are an important prerequisite for better waste management in the construction sector. The aim of this study is to investigate the differences and possibilities between static bottom-up models and parametric BIM-integrated bottom-up models for material flow analyses to predict the building material composition of historical building typologies. Findings are, when comparing the predictive capabilities of the pre-audit model with a novel implementation of a generative parametric model, that we see a drastic improvement in the error-reduction. The test models and test cases are based on limited data but given the significance of the magnitude of variance between the two models, there is a strong indication that the most precise modelling approach is obtained when utilizing a parametric model based on historical building traditions. In contrast, the use of normal static prediction-based modelling is hard to justify since data on demolition waste is of poor quality. Combining the two modelling approaches might present a new alternative to reduce factor errors in predictions of demolition waste and create a foundation for better pre-demolition audits and BIM models for material passports.

Keywords: material flow analysis (MFA); building stock; parametric modelling; construction and demolition waste; building information modelling (BIM)

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1. Introduction

The construction sector is one of the largest consumers of new raw materials, with a yearly depletion rate of 40% [1], but it is also responsible of a large share of the generation of waste, producing 34% of all waste in OECD countries [2]. In addition to its large-scale consumption of materials, the production of new building components also generates large CO_2 emissions during production, which means that 11% of all anthropogenically created CO_2 emissions can be related to the production of building components [3]. Construction is therefore an important focus area for the circular economy, where high rates of reuse and the recycling of building components and materials from the demolition of existing buildings can help reduce the need for new materials in the construction of new buildings [4]. The current reuse and recycling rates for construction waste vary widely from country to country. Some European countries have high recycling rates, but many of the heavy waste fractions such as concrete are still recycled to a low value, often being crushed as a base for roads or backfilling [5]. There are already many annual inventories of the historical production of waste from the demolition of buildings in the European Union, which are mainly driven by major international initiatives such as the 70% recycling target in European waste legislation [6], but there is still a lack of knowledge about the materials stored in the existing building stock and that will become waste at some point in the future. At the same time, embedded materials have the potential to be included in circular material flows when buildings are demolished in the future. Being able to calculate better estimates of future waste generation from the existing building stock is therefore an important prerequisite for improving waste management [7].

Material flow analysis (MFA) has been used for many years to determine the flows of materials in anthropogenic systems. If an MFA only covers a certain point in time, it is called a static MFA, whereas an MFA that considers a system over time is called a dynamic MFA. The materials embedded in a stock can be calculated using top-down or bottom-up approaches [8]. The bottom-up method considers the embedded materials in a limited part of the system and subsequently scales them up. The top-down method assesses the embedded materials by examining the difference between inflow and outflow in a system. In addition, MFA can be either retrospective by examining stocks and flows in the past based on historical data, or prospective by trying to predict developments in flows and stocks through historical data and extrapolation [9]. In terms of modelling resource flows, the retrospective top-down method is the most used [9,10], whereas the retrospective bottom-up approach is the most widely used to calculate stock flows, such as in buildings [8]. These bottom-up studies of the material composition of buildings often use a calculated material intensity, composition or mass flow for a particular typology of buildings, after which a retrospective assessment of the historical stock for that typology can be calculated, as demonstrated by [11–18]. Alternatively a prospective analysis can be added to predict future changes or outputs from that typology, as demonstrated by [19–25]. However, several studies also use a top-down model to estimate materials in the building stock by examining either in- or out-flows of materials [13,26,27]. A better coupling of bottom-up and top-down approaches with better data on material intensities and component life times is needed to increase the reliability of stock and flow estimates [28].

Although more reliable data on material intensities for buildings are needed to make accurate material stock studies, these data are not available in most countries [29]. In addition, the integration of building information modelling (BIM) into MFA can contribute to a better handling and storage of material-specific data on buildings and thereby contribute to accurate estimates in terms of the volumes of building components and materials in existing buildings [30] and the recoverability of materials [31]. One of the advantages of applying BIM may be its ability to quantify material estimates based on volumes in early design [32], whereas traditional stock estimates are mainly based on m^2 floor area [33]. Given the innumerable parameters that can define a parametric model [34], it is relevant to describe links to the typology of the building to acquire a deeper understanding of building traditions for that given typology in a parametrical sense [35]. BIM models with material data also create a better foundation for making integrated BIM-LCA calculations for assessing environmental impact of renovation of existing buildings [36,37]. Attempts to model historic buildings with BIM and parametric tools have been made in recent studies e.g., [38]. However, previous work in integrated material estimations in BIM has focus on salvaging possibilities [31], design for disassembly [39] or storing material data in BIM models [40] and has not shown in-depth typological modelling at scale with parametric tools for MFA in stock flows. This is in contrast to many recent attempts to provide high-quality quantitative take outs from BIM in planning [41–43] and arguably model-based quantity take-offs are the most valuable use of BIM in cost management of new buildings [44]. Unfortunately, (high-quality) BIM models of existing and historical buildings are rare and inaccessible.

The aim of this study is to investigate the differences and possibilities between static bottom-up models and parametric BIM-integrated bottom-up models for MFA to predict the building material composition (BMC) of existing building typologies. The objective is to identify the framework, scope and boundary conditions for (i) BMC-relevant data (ii) BMC-relevant typology and (iii) BMC-relevant predictive models. In the present study, two types of predictive MFA models for material composition are tested and analyzed. The first model is static and based on material data from pre-demolition audits in Copenhagen. The second is a generative parametric model based on data from public building registers and literature on building practices specific to historical typologies. The models are tested and compared based on four case studies.

2. Materials and Methods

The reliability of the models is analyzed for the accuracy of the prediction of BMC within the model by using statistical techniques (k-fold cross-validation and Monte Carlo simulations). Factorial dependencies outside the model are analyzed empirically and use references from the literature. High-level mathematical notification of factorial dependencies within and outside static and parametric modelling approaches are used to describe and compare the models.

2.1. Static Material-Flow Analysis

The static model uses information on individual buildings as the fundamental source of data in predicting the material composition of buildings. Similar models based on demolition data have been used in previous studies [45] to predict material flows. Static MFA is limited to describing systems at a specific time in a current state [46], feedback loops and other similar system dynamics cannot be captured from such models. Nonetheless, from this simplistic approach, we define the precision of each data point as the ability to (i) identify a building material and (ii) measure the quantity of the material.

One impractical yet straightforward way of determining the material composition of any building is to map the building waste composition (BWC) of demolitions. Buildings can theoretically be dismantled, sorted and weighed for each material composition and thus efficiently serve as the fundamental data source for BMC. It is safe to assume that two identical buildings, one having been demolished, the other still standing, have the same BMC. Based on this assumption, we can describe the translation of post-audit building waste composition from BWC to BMC for equivalent existing buildings as:

$$BMC_{eqv} \approx BWC_{post} \tag{1}$$

In the ideal world, with any model for predicting BMC for any building, the following terms are given if:

BWC data are abundant and accurate.

Equivalence derives from building typology.

Unfortunately, neither term can be assumed to be met safely with current data and current building typologies, which is why the model needs to take this into account. To generalize, the model is introduced with discrepancy factors, *f*, per material category/waste category:

$$BMC_{eqv} = f_{CD} \cdot f_{sCD} \cdot BWC_{post} \tag{2}$$

where f_{CD} and f_{sCD} are tied to the auditor and systemic components of a construction and demolition waste system, which handles the identification and measurements of the BWC (see Table 1 for a detailed description of these factors). Many different approaches have been developed to measure demolition waste system data both directly and indirectly [7] to account for such factors. We assume that a model based on the direct weights of materials at a waste sorting and handling facility will have the highest accuracy potential.

To accurately translate all the categories of materials present in a building in terms of an equivalent waste composition from demolitions, the few mandatory categories being registered in the dataset, such as the pre-demolition audit, do not explain all the materials in a building, since it is based on a professional assessment performed by an auditor. It is therefore necessary to accommodate non-registered, not-yet-registered and future-registered building (waste) material categories, BWC_d, in contrast to all the materials that are registered BWC_r:

$$BMC_{post} = BWC_r + BWC_d \tag{3}$$

Table 1. Factors/flow origins identified for BMC models.

Audit System Factors, *fsa*	**Auditor Factors, *fa***
• Approximation method for measurement of physical quantities • Approximation method for destructive and non-destructive tests on materials • Training, education, certification and support of auditors • Systemic political, financial and cultural influence	• Practical experience of various building typologies • Skills and equipment in identifying materials and amounts • Quality assurance of audits • Educational & certification level of auditor
Demolition waste system factors, f_{sCD}	**Demolition waste factors, f_{CD}**
• Method for measurement of physical quantities • Method for destructive and non-destructive tests on materials • Method for sorting and storing materials • Systemic political, financial and cultural influence (e.g., accessibility of data)	• Skills and equipment for identification of materials • Physical capacity for sorting and storage of materials • Quality assurance of C&D facility, its assessors and processes
Typological factors f_{type}	**Model-centric factors, f_{fit}**
• Method and requirements on typological categorization of buildings and materials. • Available documentation and details on structure and building envelope per typological category. • Available overlapping data to determine a building typology category, if selected category is not given in the source data set. • Typological links to historic building codes, local planning requirements, etc. • Systemic political, financial and cultural influence (e.g., non-compliance of building codes)	• Method for fitting the data to the model • Method of fitting the generative parametric model to measured data • Identification of most influential parameters that describes a typology • Implementation factors, such as possible states per parameter, choice of tools, coding language, speed, flexibility and accuracy of the implementation. • Quality assurance of waste facility, its assessors and processes.

We may rewrite the model to consider demolition waste factors for all identified categories, BWC_{eqv} as follows:

$$BMC_{eqv} = f_{fit} \cdot f_{sCD} \cdot \left(\sum_{BWC_r=1} (W_{BWC_r} \cdot f_{CD}) + \sum_{BWC_d=1} (W_{BWC_d} \cdot f_{CD}) \right) \quad (4)$$

where $BWC_r = 1$ is the building waste categories included in the waste system, and BWC_d is the materials not identified as building waste categories within this system. W_{BWC} is the measured weight of a building waste category, while W_{BWCd} is the measured weight of materials outside the identified building waste categories. f_{sCD} is the systemic errors generated due to higher-level waste conditions and management, and finally f_{cd} is the errors associated with the measurements and identification of the specific materials at the specific waste-sorting facility.

At this point, we have yet to account for the factors that apply when equivalence derives from typology, instead of assuming full equivalence between BMC_{eqv} and BWC_{post}. In other words, the results of the MFA depend on the way the typologies are grouped. If we assume some type of audit/assessment of buildings are used to determine its typology, we can adopt these errors under the two factors f_a and f_{sa} (see Table 1 for a detailed description of these factors), which account for faulty typological inspections at a varying level of detail:

$$BMC_{typo} = BMC_{eqv} \cdot f_a \cdot f_{sa} \quad (5)$$

This gives a generalized MFA baseline for BMC based on typology and BWC data:

$$BMC_{typo}\frac{1}{f_a \cdot f_{sa}} = f_{fit} \cdot f_{sCD} \cdot \left(\sum_{BWC_r=1} (W_{BWC_r} \cdot f_{CD}) + \sum_{BWC_d=1} (W_{BWC_d} \cdot f_{CD}) \right) \quad (6)$$

The typology BMC_{typo} calculated through the static MFA is based on pre-demolition audit data reported to Copenhagen Municipality, which are not publicly available. The reported pre-demolition data is based on the requirements in Waste Law BEK no. 224 from 08/03/2019 [47] and the previous version of the Waste Law BEK no. 1759 from 27/12/2018 [48]. The data contain information on demolition waste from both total and partial demolition, as well as renovations. The municipality's construction waste in the notification is reported on the address level. The notification contains quantities of waste in whole tonnes is divided into material fractions and the expected handling of the waste (preparation for reuse, recycling, other recovery or disposal). The reported data are based on a pre-demolition audit, and which material fractions and quantities were actually generated during the demolition or renovation are not subsequently checked. The data input to the static MFA model is based on data from 474 cases of demolition cases and 946 cases of renovation carried out over a two-year period from 2018 to 2019. A linear regression model for W_{bwc} using k-fold cross-validation covers 16 building waste categories ($BWC_{i,n=1}$. $BWC_{i,n=16}$) where its assumed that every W_{BWC} is independently described as:

$$W_{BWC,i} = \beta_0 + \beta_{1XBMC,i=1} + \cdots + \beta_{nXBMC,i=n} + \varepsilon_i \quad (7)$$

where β and ε are model response variables, and χ is the id of a building in the data set.

Thus, the linear predictive building material composition for each typology category, t as presented in Table 2, is described as:

$$BMC_{typo,t} = f_{fit} \cdot \left(f_{sCD} \cdot \sum_{BMC_r=1}^{i} (W_{BWC_r,i} \cdot f_{CD,i}) + \sum_{other=1}^{i} (W_{other,i} \cdot f_{CD,i}) \right) \quad (8)$$

where t is one of the first five typology categories (See Table 2) that filters the selected span of years, BWC,i represent the material categories except the category "other", which is assumed to represent the $BWCd$ fraction of the building material composition. f_{fit} represents the model-centric parameters that describe how well the model fits the data. f_{sCD} and $f_{CD,i}$ are ignored in this case and equal 1.

The static MFA is tested on two different buildings with two different typologies. Case study 1 is an office building in typology category 8, which was constructed in 1999, then demolished in 2020. The floor area of the office was 1497 m^2 excluding the basement and roof area. The office building had a single floor, excluding basement and roof. The height of the building was assumed to be 4 m, resulting in a gross volume of 5868 m^3. Case study 2 is a daycare center, constructed in 1976 and demolished in 2020. The floor area of the daycare center was 578 m^2, excluding basement and roof area. Similarly to the office building, the building had a single floor. Its height was assumed to be 4 m, resulting in a gross volume of 2312 m^3.

The registrations of waste in the pre-demolition audit for the two case-study buildings can be found in Supplementary Material Table S1.

2.2. Parametric Material Flow Analysis

The principle behind this parametric approach is the generation of a high level of detail from low-level data by utilizing rule-based modelling techniques by encoding geometric Boolean operations. While it is unfeasible to describe every set of parametric encoding in detail with mathematical notations for comparative reasons, the parametric model is summarized in Equation (9) with a description of the flow origin parameters in Table 1 and the parametric Grasshopper model can be accessed in raw encoded form (see Supplementary Material Table S2). To assess the results comparatively for our test models, a set of procedurally connected requirements is defined to validate the model's implementation. These requirements, which are meant to systematically reduce errors from model-centric factors represented by the factor f_{fit} are associated with the choice of typology (in this case, limited to buildings from the period 1851–1930, typology category two; see also Table 2).

Table 2. Danish typology based on construction periods in TABULA [49] focusing on energy requirements. BR is the Danish Building Regulations.

Construction Period	Changes in Typology	Typical Materials	Typology Categories
Before 1850	Shift in building tradition	Masonry, Thatched, Wood beams	1
1851–1930	Shift in building tradition	Masonry, Tiles, Wood beams	2 Case study 3 & 4 (parametric MFA)
1931–1950	Cavity walls introduced	Masonry, Tiles, Wood beams	3
1951–1960	Insulated cavity walls introduced	Masonry, Eternit, Wood beams	4
1961–1972	First energy requirements in BR1961	Masonry, Concrete bricks, Tiles, Eternit, Wood beams	5
1973–1978	Tightened energy requirements in BR1972	Masonry, Concrete backwall, Eternit, Tiles, Wood beams	6 Case study 2 (static MFA)
1979–1998	Tightened energy requirements in BR1978	Masonry, Tiles, Concrete backwall, Eternit, Wood and Concrete beams	7
1999–2007	Tightened energy requirements in BR1998	Masonry, Tiles, Concrete backwall, roof, Wood, Steel and Concrete beams	8 Case study 1 (static MFA)
2007–2011	Tightened energy requirements in BR2006/2008	Masonry, Tiles, Concrete backwall and roof, Wood, Steel and Concrete beams	9

The parametric model, based on an extensive collection of articles on typologies in Denmark, is mapped and curated by BYG-ERFA [50], combined with detailed descriptions of multi-story residential buildings categorized by typology 2 (see Table 2) [51,52]. Input from the Danish national building register (BBR) [53] includes area, number of floors, building age, outer wall materials, roof materials, building footprint and free parameters identified. This leads to the following approach to selecting influential parameters for the parametric model:

1. Generate a complete 3D model of essential building elements through the 11 steps shown in Figure 1; foundations, load-bearing walls, load-bearing decks and roof structures for a given typology based on definitions and rules defined by Engelmark and input from BBR implemented with the least amount of free parameters.
2. Calculate volume of generated building elements. Each element is assigned with material id based on [49] and amounts are calculated based on generic densities. For known parameters, each parameter is chosen by the state given the dataset BBR for that particular building in question. For unknown parameters (not present in BBR), each parameter includes variance and boundaries for the Monte Carlo simulation approach. The variances in our test case are derived from a small test/training set of carefully measured building material compositions.
3. The results of the building material composition generated from a building is recorded in two formats, one for human inspection (for visual inspection, 3D models, and 2D renders), for comparison with photos; the output, in this case, shows the most likely (summarized median) of all possible parameter states. The second forma is a machine-

readable file format for further processing and boundary checks with pre-modeled sets of buildings with a given typology.

4. While the algorithm used to generate the 3D model is implemented to present the most probable constructions and materials (based on its available data set), it is possible to adjust the settings for the algorithms. Based on human inspection for comparison with land sat photo material (Google maps), changes to the fixed and free parameters are modified (see Figure 2), thus generating a new model through step 13 in Figure 1. This process can be repeated until the user's visual inspection has been satisfied.

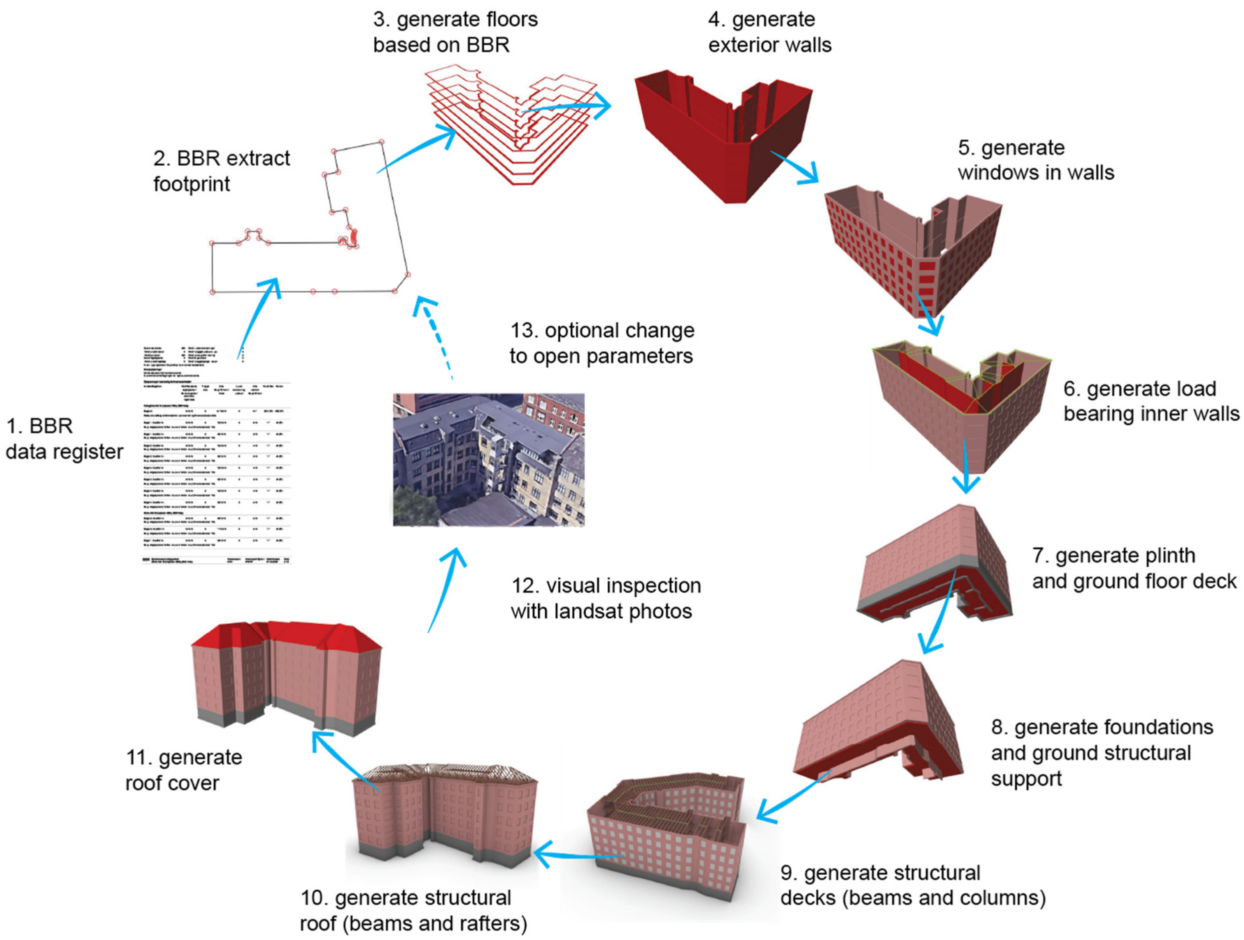


Figure 1. Step by step guide to the auto generation of the parametric BIM model with assignment of specific building components based on typical historical building practice.

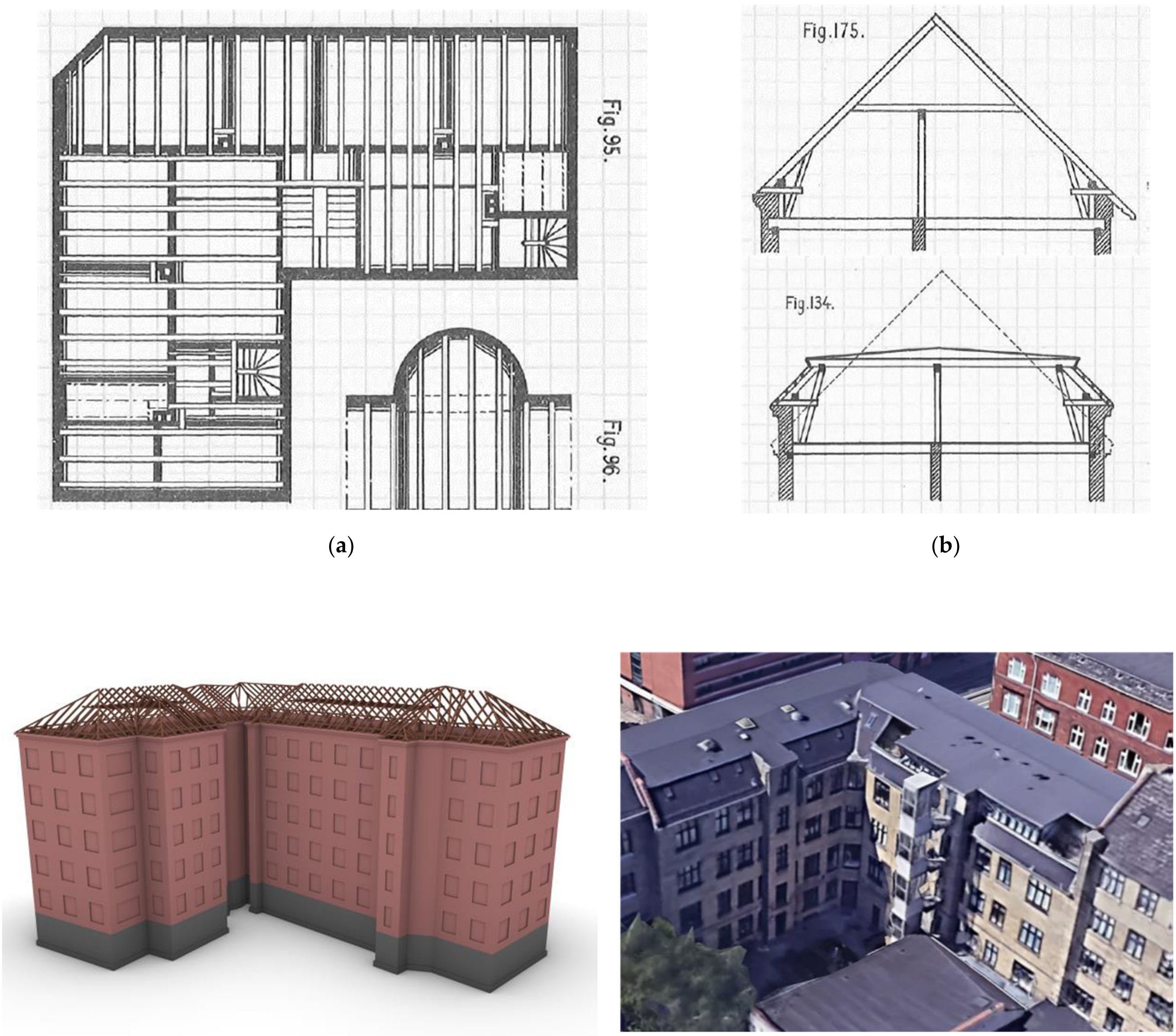
Each parameter is either modelled with a standard uniform normal distribution (P (X > 1.96)) or through a cumulative function given by the distinct value for the parameter assigned by the probability between 0–1, depending on how many times it occurs. The BMC for typology 2 is described as:

$$BMC_{typo,t} = (Fh, WH, WW, BH, FH, FDT, MCH, RH) \cdot f_a \cdot f_{sa} \quad (9)$$

where each of the variables FH to RH described in Table 6 depend and are modelled parametrically using Grasshopper3d. f_{fit} represents the model-centric parameters that describe how well the model fits the data. f_a and f_{sa} are modelled by introducing variance determined by using the one-at-a-time (OAT) simulation principle, as each parameter is simulated 300 times based on the Monte Carlo selection. Inner alignment of the model sensitivity index is calculated for each parameter. The sensitivity index is calculated using the all-at-a-time (AAT) simulation principle, where all parameters are varied simultaneously based on a set of 500 as defined by [54]:

$$S(P_i) = \frac{\frac{1}{n}\sum_j^n |y_{ij} - \beta|}{\sum_j^n \left(\frac{1}{n}|y_{ij} - \beta|\right)} \quad (10)$$

where i is the index of the parameter, n is the state of the parameter P. x_i, y_{ij} are the outputs of the system for the jth measure of x_i, k corresponds to the number of parameters and β is the base solution.



(**a**) (**b**) (**c**) (**d**)

Figure 2. Based on typological rules and drawings, typical floor for typology (**a**), and typical roof build-up several alternatives for the typology (**b**), it is possible to generate a full 3D representation of a building (**c**). The visual inspection shows that the BIM generated roof (**d**) is of the wrong type of the two typical roof construction alternatives, meaning changes of specific fixed or free parameters need modification.

Case study 3 is a residential building in typology category 2, it was constructed in 1895 and is still in use. The floor area of the building is 2003 m^2, excluding basement and roof area. The residential building has four floors, excluding basement and roof. Detailed historic drawings are used to assess the accuracy of the model, but they are not used as input in modelling the case study.

Case study 4 is a residential building in typology category 2, constructed in 1903 and still in use. The floor area of the building is 1467 m^2, excluding basement and roof area. The residential building has five floors, excluding basement and roof. Detailed historic drawings are used to assess the accuracy of the model, but they were not used as input in modeling the case study.

3. Results and Discussions

3.1. Accuracy of the Static Stock Flow Model

In general, we see how the model overshoots minerals (stone, concrete and ceramics), iron and metal. On average, for the two cases, the model overshoots by a factor of 2 and a factor of 100, respectively (see Table 3). The static stock flow model based on typology and age is unfit to describe the nuances of materials in buildings, at least based on currently available data. Depending on the building typology, the waste composition on wood can cause inaccurate predictions with a factor of 2–3. The static MFA model poorly depicts concrete, iron and metal, natural stone and unglazed bricks in general. All building waste categories typically found in large amounts (weight-wise) come with significant variance when predicted across all typologies. Even with a relatively large data set, the quality of this particular data set differs critically in serving as accurate predictors. Two mechanisms explain the high variance: (1) poor data quality (with a high noise ratio serving as prior for the model) and (2) the spread of typologies vary significantly within the data, meaning that the typologies show low internal correlations and/or are falsely identified by the filter (address, building age, type, size). Both mechanisms result in offshoots of actual BMC with an unknown but assumingly high margin.

Table 3. Two cases comparing predicted building material compositions vs. actual measured building material compositions.

	Case 1: Office Building		Case 2: Daycare Center	
	Actual BWC_r [kg/m^3]	**Predicted BMC_r [kg/m^3]**	**Actual BWC_r [kg/m^3]**	**Predicted BMC_r [kg/m^3]**
Minerals	281.1	335.8	49.0	182.1
Iron and metal	0	15.5	4.8	116.2
Wood	3.6	1.2	3.6	6.7
Total (BWC, BMC)	291.8	403.6	161.4	384.4

These variances are very high, and one should be cautious in relying on such data and models. Given the quality of the data set, we expect high variance outputs, making the approach is imprecise and challenging to apply in practice. However, since 2020 regulatory changes in the ways data are collected and verified are likely to improve data quality in the future. Thus, the method of predicting BMC from BWC using static MFA cannot entirely be ruled out. However, until much more accurate data become available, the presented type of predictive model will deliver significant forecast errors of building material stock.

3.2. Factorial Dependencies of the Static Stock-Flow Model

The variance across all buildings in the test set related to f_{fit} in the model is expressed by the mean absolute error (MAE) per material composition (see Table 4). While we do not have supporting data to derive the real f_{sCD} and f_{CD} in detail for all the data points in question, we tested the model against two waste audit cases. These present the measured building material waste composition measured by a demolition company versus the predicted waste BMC, i.e., the BWC, assuming all materials are accounted for. This gives an idea of the prediction variance (associated with the factors f_{sCD}, f_{CD} and f_{fit}).

Table 4. Post demolition BMC model and its MAE.

$BMC_{typo,1–5}$	$MAE_{Typo,1–5}$ [ton]	$MAE_{Typo,2\ Only}$ [ton]
Natural stone, e.g., granite and flint	4.0	1.1
Asphalt	95.0	10.3
Concrete	545.0	495.3
Asphalt and concrete mix	4.0	0.5
Natural stone, unglazed tiles and concrete mix	148.0	343.0
Gypsum	10.0	1.1
Iron and metal	233.0	45.4
Glass	9.0	0.4
Unglazed brick and tiles	147.0	52.6
Roofing felt	2.0	0.7
Stone wool	9.0	0.9
Wood	11.0	38.5
PVC	0.2	0.0
Plastic	0.1	0.0
Cardboard	0.03	0.0
Others	24.0	4.7

To quantify the margin of error due to audit practice and the practitioners in an audit system that may serve as much better predictions in a future data set, we conjecture that other audit systems within the demolition sector may give insights into the approximate factors of f_{sCD} and f_{CD}. As an example, we use the experience of the Danish energy-labeling scheme. Its purpose is to rank buildings on their energy use and to help the authorities regulate the energy consumption of buildings according to EU 2018/844 [55]. The system is composed of a certification standard maintained by a nationally regulated organ (Danish Ministry of Environment), which places a high authority level on the system itself but is handled through certified companies and their auditors. Data on inspection of these certifications are available in a public energy label database, which makes it possible to inspect and compare audits and take out random inspections of audits to incentivize measurements that are more accurate. Audits are based on version-controlled guidelines for auditors, which challenge the comparability of audits over time. This has contributed to criticism of the system because 23% of audits in 2018 contained errors that would affect the result so much that the energy label had to be changed [56]. Because the system does not explicitly include materials, the materials' volumes can only be extrapolated from the building envelope and not from the rest of the building composition.

This same kind of error rate of 23% can be associated with the errors that are chargeable to audit-system factors and auditor factors. Given this assumption, the material composition is based on audits using a similar approach, and the given audits can take into account equivalent measurements of interior building surfaces (floors, inner walls, etc.) and BMC for the entire building.

To generalize further, we surmise that BMC from audits will contain around 20% inaccurate information caused by systemic errors and errors due to the specific auditor, equivalent to those reported by [56]. We can further speculate if auditors who are trained systematically on differences in typologies will reduce f_a-inaccuracies. While these errors are likely to be minimized, with a higher frequency of quality assurance and better training of auditors, the model suggests that divergences between audited material compositions and "true" material compositions cannot be minimized, since no term for feedback is introduced. This sets up a BMC model approach for high-precision measurements of material waste compositions based on post-demolition data, as introduced in the regulatory change to how to manage BWC, mentioned earlier.

3.3. Accuracy of the Parametric Stock-Flow Model

Compared to the static MFA, we obtain more accurate predictions for all materials with the parametric MFA (see Table 5). The highest recorded errors are for concrete, again consistent with the static MFA model, but in this case the variance is much smaller, and the predictions are more consistent compared to the pre-audit model using BBR data as its prior. This suggests that rule-based parametric models generate reliable quantities and/or identify materials significantly better than a somewhat unregulated pre-audit system as that represented by the demolition waste measured data set.

Table 5. Building material composition for two cases, actual vs. predicted.

	Case 1: Mølle Alle		Case 2: Brysselgade	
	Actual BMC [kg/m^3]	**Predicted BMC [kg/m^3]**	**Actual BMC [kg/m^3]**	**Predicted BMC [kg/m^3]**
Masonry	179.1	179.3 +/− 12.5	192.6	193.9 +/− 33.3
Concrete	102.2	104.1 +/− 7.0	110.3	111.5 +/− 19.3
Wood	39.0	39.6 +/− 2.7	41.9	42.2 +/− 7.2
Iron/Steel	13.5	13.5 +/− 1.0	13.1	13.3 +/− 2.2
Total (~BMC)	333.7	336.5 +/− 23.1	357.9	361.0 +/− 62.0

The parametric model also generates a deeper typological breakdown than what is possible to generate from the BBR set alone. The "typologysation" is equivalent to the number of open parameters in the model. This allows for a selective tweaking of the generated building components and their material compositions adjusted for all other parameters. The primary benefit with the parametric MFA ties in with the qualified opportunities for component types linked with the option to visually inspect the building in the model. This is currently not possible in the static MFA approach.

3.4. Factorial Dependencies in the Parametric Stock-Flow Model

To explain the model's insights, we show the simulated variance along with the sensitivity index of each relevant parameter in the model. Three distinct experiments were performed with 100 simulations each. The analysis took place individually on the parts of the building that had significant variance during the uncertainty analysis. For masonry, the floor height, the height and cantilever of the wall, and the window area were selected as open parameters. Specifically relevant for concrete, there were variations in basement height, foundation height and width, and deck thickness. In the roof construction, the height and cantilever height of the wall, the roof slope with a uniform slope, slopes with a two-part roof slope and the roof height varied.

Inaccuracies due to floor heights were mainly caused by the differences in the BBR data for declared areas vs. generated areas based on a polyline-footprint multiplied by the number of floors (see Table 6 column 2). We see the majority of errors as linked as expected to the BMC of the façade and not the internal structure or the foundation. The generative model itself had a mean absolute error ranging from 0.03 to 102.15 tonnes, where heavy materials such as masonry and concrete have larger mean absolute errors, which is consistent with the pre-audit results. Of the two cases (tested against the model; see Table 6 column 4) we saw a lower mean error than in the model (see Table 6 column 3). This was expected, as the buildings in the test set are likely to be closer to mean values than the outliers, due to the limited test set used.

What remains relevant to conclude is that, when the model generates buildings that resemble the "correct typology", its expected variance is reduced significantly, and highly accurate predictions can be made. At the same time, this also means that if the model attempts to predict BMC outside its actual typology, the predictions will almost certainly be less accurate. The case studies in the test set summarize the BMC for primary structural materials (material compositions), as shown in Table 7.

Table 6. Essential free parameters identified for housing constructed between 1931 and 1950.

Parameter	Parameter Type	Mean State [m]	Variance, OAT [m]	Sensitivity Index, AAt [-]
Floor height, Fh	Cumulative function	3.20	0.117	0.39
Window height, Wh	Uniform distribution	1.80	0.274	-
Window width, WW	Uniform distribution	1.40	0.016	-
Window area (derived)	Uniform distribution	-	-	0.45
Basement height, BH	Cumulative function	2.80	0.018	0.26
Foundation height, FH	Uniform distribution	0.50	0.008	0.27
Foundation deck thickness, FDT	Uniform distribution	0.30	0.528	0.41
Mural crown height, MCH	Cumulative function	0.65	0.0135	0.12
Roof height, RH	Cumulative function	2.70	0.0837	0.20

Table 7. Errors due to generative parametric modelling factors.

$BMC_{typo\ 2}$	MAE (f_{type}) [ton]	MAE (f_{fit}), in Model [ton]	MAE (f_{fit}), Test Set [ton]
Masonry	20.8	102.15	2.30
Secondary masonry	0.0	11.65	2.00
Concrete	4.0	55.65	10.75
Wood beams t1	0.0	1.00	−0.03
Wood beams t2	0.0	9.61	0.04
Wood rafters t3	0.3	2.04	0.23
Wood roof t4	0.0	0.39	−0.01
Wood laths t5	0.0	0.03	−0.02
Steel profiles	0.0	1.53	0.05

3.5. Predictive Capabilities of the Pre-Audit Model and the Generative Parametric Model

To begin with, we see that the methods determining the relevant factors that affect the accuracy of harvesting BMC vary significantly between the approaches we present in this paper. The models are based on different data sets, but they also refer to different domains of modelling that are rarely seen in the same research projects. Since the models range from direct data transfer based on low-level multiclass linear regression to high-level generative parametric models, we chose to focus on the most critical aspects of our experiments' model results and indications.

Several test implementations of the parametric algorithms have been performed including different ways of generating the structural beams at every floor as shown in Figure 3. During these tests cases studies were used to calculate the errors on BMC for the beams.

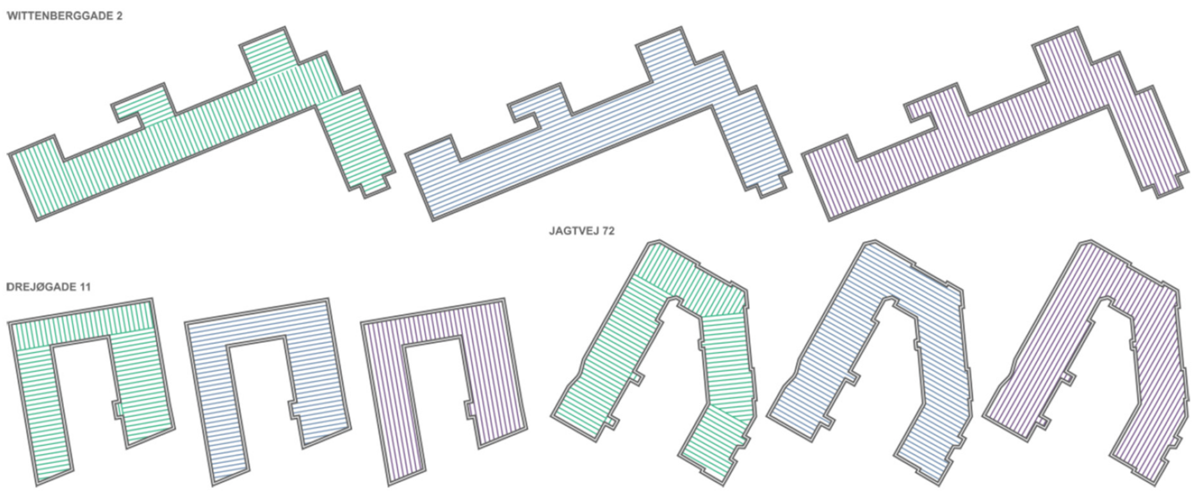


Figure 3. Beam span algorithm test, here showing three buildings actual span (green) and two different implementations tested (blue and purple).

Summing up, we suggest that factors can be classified similarly, regardless of the modelling approach. The models all share the same distinction between two types of factor:

The quality of direct measurements of building material compositions from material waste composition is a result of the following factors:

- Demolition waste system factors associated with the method of measuring construction demolition waste made by the waste-handling facility.
- Demolition waste factors associated with the specific waste-handling facility.

The quality of building material compositions by indirect measurements performed through audits is a result of two types of factor:

- Audit system factors associated with an established building audit system.
- Auditor factors associated with the specific auditor.

The quality of generated building material compositions from a parametric model of BMC is a result of the following factors:

- Typological factors associated with historical and cultural factors.
- Model-centric factors associated with the method of modelling.

We have shown that, when predictive modelling is used, the model-centric factors (f_{fit}) are easier to quantify compared to the systemic factors e.g., f_{sa} and f_{sCD} and the "human in the loop factors", such as f_a and f_{CD}. Nonetheless, it is possible to quantify such factors. When this can be done, interventions can be introduced to reduce their inaccuracies.

When comparing the predictive capabilities of the pre-audit model with the generative parametric model, we see a drastic improvement in the error-reduction of f_{fit}. Our test models and test cases are based on limited data, and the model's data priors are not directly comparable. However, given the significance of the magnitude of variance between the two models, we see an indication of a more precise modelling approach when utilizing a parametric model. The consequence of a pre-audit model that relies purely on the statistical significance of its raw data is the acquisition of good-quality data. We see that the pre-audit model is highly susceptible to errors in the waste pre-demolition audit even after heavy pre-processing of the data. In addition, the material intensities for existing buildings have increased due to the growing amount of material that is used for replacements [57], which will not be reflected in the results when the data is historical. We also see that the number of individual building data points in every typology category matters for the precision of the model. The generative parametric model can be based on testing the implementation of typology 2, defined on the basis of a relatively small prior data set, as long as the parametric rules are realistically accounted for in the model. This, however, does not mean that every typological category is equally well defined or that it can be described with few and efficient parameters derived from other datasets (i.e., BBR). It is unlikely that, e.g., typology category 4 can be modelled with as few parameters as we present for typology 2, simply because typology 4 ranges much further in material choices and building traditions.

Without speculating whether the models are likely to be transferred to other cities and countries, we do suggest that if other countries were to rely on similar ways of collecting waste data through pre-demolition audits, they would find that currently available data on demolition waste is of such bad quality that static prediction-based modelling is hard to justify. It would therefore be better to use the parametric approach, that, given (a) well-defined sets of rules and (b) an accurately assessed typology, BMC can be predicted with high levels of precision. This assumes that the BMC calculated from technical drawings and rules actually does account for the built BMC.

3.6. Implications for Future Predictions of Material Composition and Registration of Waste Data

It seems a natural step to develop better techniques and methods to fit existing buildings into distinct typologies and possibly rethink the typological systems used internationally. We found that TABULA lacks detailed information on BMC but supports derivatives of expected materials used in the mapped typologies. A systematic use of existing typologies in TABULA, combined with other sources of BMC-relevant data is possible, as shown in this paper, but our results indicate that a more "fine-grained" version of TABULA would further improve the model's predictions.

This situation has since changed through the revision of waste legislation BEK no. 2159 from 09/12/2020 [58]. From 2021, upon notification of a pre-audit, each case is given a serial number, which must be reported to the waste management center to which the demolition waste is being delivered according to the new added paragraph § 76 [58]. Data on this regulatory change are sparse and have not been used in the following analyses.

There is a need to further develop the model's predictive capabilities by reducing the model-centric factors of f_{fit} using more advanced machine-learning models (for the pre-audit approach) or more complex parametric models that can combine ever more data from several sources. However, we stress that we simply cannot wait until data on demolition waste is "good enough" to make useful BMC predictions. If society is to transition into a circular economy within a few decades, and if data collected through current waste handling facilities does not improve, we shall be unlikely to acquire the necessary knowledge of BMC at the level of future reuse and recycling at scale for a circular economy. Thus, new ways of efficiently and accurately measuring BMC are needed to establish a better "ground truth" for any bottom-up approaches to predictive modelling. That said, we find that, over time, data from demolition waste, combined with established systems such as waste pre-audits, will be an important source of BWC data that can be used to extrapolate from similar typologies to existing building stock.

One interesting aspect of the different models is the synergy between them. If deployed widely in practice they can be used to reduce factor errors. Future BWC data are expected to give much more precise BMC data, thus creating an opportunity to confirm/challenge pre-audit data when buildings are torn down or renovated. It is possible that in time auditors will benefit from the more precise waste data to form predictions that are more precise for the BMC of buildings that are still standing. Ideally, some such system will be created without direct rebukes from auditors and will be set in place to help and justify specific methods of measurement and ways of identifying materials. Such a system will work if it creates indirect feedback made through the baseline from the generative parametric BMC, rather than purely based on infrequent feedback from the waste-handling facilities of demolished buildings, as shown in Figure 4.

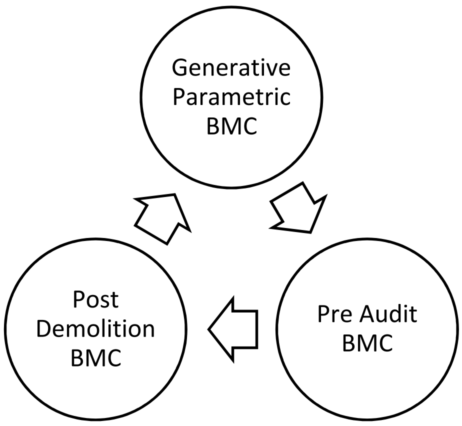


Figure 4. BMC synergies to improve reliability in material prediction between the post demolition BMC and future predictions of BMC.

The advantage of such set-up is that BMC can be generated for all buildings nation-wide, while knowing that some buildings have been falsely categorized (by typology) and that input data are poorly depicted in the relevant databases. Auditors can step in and correct the typology, further enhancing the BMC by means of qualitative identifications and measurements. This helps to improve and calibrate the parametric model from two directions, from the auditors' assessment side and the actual BWC = BMC test when the building is demolished. Given continuous recalibration and improvement of generative parametric models, $f_{fit} \rightarrow 0$ across the models, which states that we can assume more precise BMC, thus making the potentials for urban mining and recovery more reliable.

4. Conclusions

The aim of this study was to investigate the differences and possibilities between static bottom-up models and parametric BIM-integrated bottom-up models for material flow analyses to predict the building material composition of historical building typologies. Hereby we also investigated the inner factorial dependencies of material flow analysis on predictions of building material composition by a static and a parametric model. Among the factors identified are the mechanisms related to the systemic impacts of auditors and waste-handling facilities, the factors associated with specific methods of measuring material composition and the particular model's ability to represent the available data. The results show the key differences between a static bottom-up modelling approach and a parametric BIM-integrated bottom-up modelling approach for material flow analyses of historical building typologies. When comparing the predictive capabilities of the static model with a parametric model we see a drastic improvement in the error-reduction of material flow predictions. While the parametric model is more reliable in quantifying building material compositions, it is also has the potential to improve over time with new and better implementations. The study concludes that a more precise modelling approach is obtained when utilizing implementations of heuristic and statistic historical building tradition documentation specifically addressing a narrow building typology and when elementary data of key parameters (such as number of floors) are consistent when delivered by a public data set. Furthermore, the results shows that demolition waste data is of poor quality and in itself is prohibiting useful quantity predictions of building material compositions on existing building stock. While it is expected that future waste data are more reliable, the article argues for a combined static and parametric modelling approach to reduce factor errors in predictions of demolition waste. This can be used as a proxy for creating more precise pre-demolition audits and BIM models for material passports to support a circular construction transition.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings12091423/s1, Supplementary Material Table S1, Supplementary Material Table S2, Supplementary Material_2_Parametric_Model.

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Conference Paper 1

CP1: Multi-criteria analysis of buildings transformation potential in planning and design.

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Multi-criteria analysis of buildings transformation potential in planning and design

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ABSTRACT: A large part of the existing building stock in Europe was built before 1980 and is now facing significant renovation and energy-related optimisations, which are focus areas in political initiatives such as the EU's new Green Deal and Renovation Wave. However, not all buildings can be used for the same purposes as when they were built. This raises the question of what can be transformed and what needs to be demolished. The motivation is to reuse as many existing structures as possible to decrease the need for new materials, as well as waste from components and materials removed from the buildings. However, decisions on whether to transform or renovate need to be based on good-quality information and data during planning and design in order to choose the design strategies that provide the building owner with value and motivation. In the following, a method for providing information about the transformation potential is described, developed and tested in the framework of CIRCuIT, an EU Horizon programme project. The transformation potential tool identifies the twenty most used indicators for assessing transformation and flexibility. These are then evaluated through case studies of existing buildings. The results shows that the differences between using the twenty most recognized indicators and a broader set of 64 indicators is small, which shows that it is possible to make timely and cost-effective visualizations of the transformation potential for buildings that can be used as a basis for decision-making in the early planning phases.

1. Introduction

Construction is among the sectors that have the most significant negative impacts on the environment. Large-scale energy consumption in the operation of buildings and the environmental impact of the production of new materials are responsible for around 40% of artificially created global CO_2-related emissions (UNEP, 2019). In addition, the construction sector also generates large amounts of waste from the renovation or demolition of existing buildings and from mismanaging construction materials. A large part of the existing building stock is outdated, which creates a need to increase the number of renovations, focusing on energy reductions and improvements to indoor climates (Alba-Rodríguez et al., 2017). This could potentially lead to a high increase in the demand for new materials and the generation of larger amounts of waste from components and materials removed from the buildings. The solution to the problem may be to discourage demolitions by repurposing a broader spectrum of buildings through transformations. Several studies indicate that there are both environmental and economic benefits in renovating and transforming buildings compared to demolishing them and replacing them with new low-energy buildings (Murray et al., 2020; Remøy et al., 2007). A large part of the existing building stock was built before 1980 and is now facing significant renovation and energy-related optimisations, which are also focus areas in political initiatives such as the EU's new Green Deal (European Commission, 2019). Decision tools and methods that can be used to assess the renovation and transformation potential of existing buildings cost-effectively and straightforwardly in the pre-design and planning phases are essential (Nielsen et al., 2016) when it comes to providing early information about opportunities to reuse entire buildings and thereby minimize the risk of demolition. This study aims to establish and test a simple assessment tool for quantifying the potential of buildings for transformation and flexibility. The transformation potential tool is established and evaluated through i) literature studies of indicators and methods for assessing transformations, ii) the establishment of a framework for the evaluation of transformations with associated indicators, and iii) demonstrations of usability by means of a case study.

2. Literature study OF indicators relevant for assessing transformation and flexibility

In Denmark, the SAVE (Survey of Architectural Values in the Environment) method has been used to designate buildings worthy of preservation since it was introduced in the 1990s (Tønnesen, 1995). In this method, buildings are assessed in audits based on the following criteria: 1) architectural value, 2) cultural or historical value, 3) urban identity value, 4) originality value, and 5) condition value. Each criterion is rated on a scale from 1 to 9, where 1 is the best value. Subsequently, an overall score is calculated for the building, which becomes the preservation value. A score of 1-3 is described as a high conservation value, which can affect which renovations can be applied to the building, and a SAVE score above 5 increases the risk of demolition. In Denmark, there are currently SAVE evaluations for only 360,000 buildings (Kulturarvsstyrelsen, 2011) out of the total building stock of 2,251,365 buildings (Statistics Denmark, 2021). In addition, many SAVE evaluations are outdated, as they have not been updated since the method was introduced in the 1990s.

In relation to the research presented here, the SAVE value is relevant as an indicator because conservation values are one of municipalities' most frequently used indicators for designating which buildings are to be demolished and which are to be preserved.

There are already various methods and indicators for calculating transformation and flexibility. One framework for assessing the transformation of buildings, established by Durmisevic (Durmisevic, 2016), consists of fifteen building-level indicators for calculating transformation potentials (see Table 1), where all indicators are divided into four categories: dimensions, position, disassembly, and capacity. However, this framework does not describe the rating criteria for the various indicators. Geraedts and Voordt (Geraedts et al., 2008) have set up a building feasibility-scanning tool for office buildings that contains 23 indicators at site level and 28 indicators at the building level. The tool they developed includes both a description of the evaluation criterion and the data source. When using the tool, a decision must be made as to whether the various measures have been met. If a criterion is met, a "Yes" must be entered next to the indicators. Then all the met criteria are counted together. An overall transformation score for buildings is calculated on a scale from 1-5, where 1 indicates excellent transformability, 3 limited transformability and 5 no transformability.

Table 1. Identified indicators drawn from the literature study on assessments of transformation and flexibility.

(Durmisevic, 2016)	**(Geraedts et al., 2008)**	**(Geraedts, 2016)**	**DGNB (ECO2.1 + TEC1.4)**
Dimensions on building level	Office building recently built	Surplus of site space	Space efficiency
Dimensions on unit level	Recently renovated as offices	Multifunctional site/location	Ceiling height
Floor to ceiling height and floor thickness	Vacancy: some office space still in use	Available floor space of building	Depth of floor plan

Corridor width	Vacancy: building unoccupied < 3 years	Size of floor buildings	Vertical Access
Dimensions of the facade openings	New dwelling units can be made	Horizontal zone division/layout	Floor layout
Position of the loadbearing elements	Extendibility: horizontally extendable	Presence of stairs/elevators	Structure
Position of the vertical installation ducts	Extendibility: extra storeys (insufficient load-bearing capacity)	Extension/reuse of stairs/elevators	Building services
Clustering of the vertical elements within the buildings	Extendibility: basement cannot be built under building	Surplus of load-bearing capacity	Access and spare spatial capacity in technical centres
Accessibility to the main installation net	Building's condition	Shape of columns	Adapting operating temperatures to incorporate regenerative energies
Accessibility to the installation distribution net	Dimensions: depth of building	Positioning of facilities' zones and shafts	Suitability of lift system for later change
Separation between static and variable building elements	Dimensions: module of support structure < 3.60 m	Fire-resistance of main bearing construction	System integration across relevant trades
Capacity in relation to expansion of the building	Dimensions: distance between floors	Extendible horizontal building/units	
Capacity of the installation ducts	Support structure condition	Extendible vertical building/units	
Capacity of the loadbearing structure	Façade/openings not adaptable	Insulation between stories and units	
Capacity of the vertical communication elements	Windows cannot be reused or opened	Dismountable facade	
	Impossible to install (sufficient) service ducts	Daylight facilities	
	Presence of large amounts of hazardous materials	Insulation of facade	
	Acoustic insulation of floors < 4 dB	Measure and control techniques	
	Thermal insulation of outer walls and/or roof	Surplus capacity of facilities	**BREEM**
	<10% of floor area of new units receives incidental daylight	Distribution facilities	Accessibility: easy replacements of fabric and structure
	No lifts in building (> 4 storeys)	Location of heating and cooling facilities	Accessibility: inclusion of facilities management

	No (emergency) stairways	Disconnection of components	Accessibility: easy replacements of interior design
	Distance of new unit from stairs and/or lift	Accessibility of components	Spatial adaptability: location of structural components within the floor space
		Independence of user units	Spatial adaptability: layout in standardized grids
		Multifunctional building	Spatial adaptability: use of inherent finishes to allow replacement
		Removable units	Spatial adaptability: use of standardized material sizes
		Removable walls	Expandability: increase building capacity
		Removable inner walls	Expandability: enable future expansion and adaptation
		Possibility of suspended ceilings	Expandability: potential future functional requirements
		Possibility of raised floors	Expandability: efficient use of space to increase occupancy

These indicators are repeated in a new tool that has been also developed by Geraedts (Geraedts, 2016), called FLEX 4.0. Here, the tool has been further developed into 44 indicators divided into five categories: site, structure, skin, facilities, and space plan. In addition, the tool has also been designed to evaluate both office and school buildings. The two sustainability assessment systems, BREEM and DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen), both contain indicators for assessing adaptability. In BREEM, the indicators are divided into the categories accessibility, spatial adaptability and expandability. The indicators are also divided between structure, services and interior design. In DGNB, the indicators are divided into the categories flexibility and adaptability according to the ECO2.1 (DGNB GmbH, 2020a) evaluation criteria and adaptability of technical systems according to the TEC1.4 (DGNB GmbH, 2020b) criteria.

3. Method for establishing a tool for assessing the transformation potential of existing buildings

Based on the literature study, the twenty most frequently used indicators are selected for the transformation tool shown in Table 2. The indicators are then grouped into four categories, also based on results from the literature study. Where possible, the criteria for evaluating the various indicators are based on the criteria set out in the DGNB weighing and scoring system. For indicators where no criteria are matched in the DGNB evaluation criteria, a thorough study has been made to find criteria in other research-based systems and tools. Examples include standards such as the Danish regulations for accessibility conditions in new construction (Acosta et al., 2016) and the European energy label for buildings (for the window element of the façade). Qualitative criteria that are relevant for existing buildings are included, also based on literature study (qualitative criteria qualitative assessments such as SAVE).

Table 2. Selected indicators and associated rating criteria for a transformation potential tool.

Dimensions and Flexibility				
		3 points	**2 points**	**1 point**
***1)** Free room height measured from floor to ceiling*	Same for all	≥ 3.00 m	≥ 2.6 m	< 2.60 m
***2)** Building depth from exterior wall to exterior wall*	Office	12,50 m ≤ building depth < 14,50 m	10,00 m ≤ building depth < 16,50 m	10,00 m > building depth > 16,50 m
	Educational	-	-	-
	Childcare	-	-	-
	Housing	building depth < 11.5 m	11,5 m ≤ building depth < 13,5 m	building depth ≥ 13,50 m
	Hotel	12.5 m ≤ building depth < 14.5 m	10.0 m ≤ building depth < 16.5 m	10.0 m > building depth > 16.5 m
	Shops	-	-	-
***3)** Corridor width*	Same for all	Corridor width ≥ 1.80 m	Corridor width ≥ 1.5 m	Corridor width ≥ 1 m
***4)** Window proportion of the facade*	Same for all	< 20%	< 40%	≥ 40%
***5)** Distance between technical shafts*	Office	< 20 m	30-20 m	> 30 m
	Educational	< 20 m	30-20 m	> 30 m
	Childcare	< 20 m	30-20 m	> 30 m
	Housing	< 10 m	10-15 m	> 15 m
	Hotel	< 10 m	10-15 m	> 15 m
	Shops	< 20 m	30-20 m	> 30 m
Position and Adaptability				
***6)** Vertical access to the building*	Same for all	(gross floor area / number of access cores) ≤ 400 m2	(gross floor area / number of access cores) ≤ 1200 m2	(gross floor area / number of access cores) > 1200 m2
***7)** Adaptability of technical installations*	Same for all	Can be expanded without extensive constructive changes	Can be expanded with minor constructive changes	Can only expanded with extensive constructive changes
***8)** Non-load-bearing facades*	Same for all	Yes	Partly	No
***9)** Modular systems have been implemented*	Same for all	Yes	Partly	No
***10)** Horizontal zone division*	Same for all	3 > building functions	2 ≥ building functions	1 building function
Disassembly and Accessibility				
***11)** Accessibility to installations*	Same for all	Good	Sufficient	Bad
***12)** Easy replacements of building components*	Same for all	Good: can be removed by hand or with simple tools	Sufficient: in addition to manual work, also requires some cutting or grinding	Bad: separation that can only be done destructively with heavy machinery
***13)** Presence of hazardous materials*	Same for all	≥ 1987	≤ 1949	1950-1986
***14)** Energy efficiency*	Same for all	A2020-A2010	B-D	E-G
***15)** Condition of the building*	Same for all	Good	Sufficient	Bad
Capacity and Expandability				
	Office	≥ 75%	≥ 48%	< 48%
	Educational	≥ 75%	≥ 48%	< 48%

16) *Space efficiency: usable area (NA) / total gross area (SBA)*	Childcare	≥ 75%	≥ 48%	< 48%
	Housing	≥ 80%	≥ 60%	< 60%
	Hotel	≥ 70%	≥ 43%	< 43%
	Shops	≥ 90%	≥ 70%	< 70%
17) *Capacity of the load-bearing structure (sufficient load-bearing capacity for extra floors)*	Same for all	Yes	Partly	No
18) *Capacity of the installation ducts*	Same for all	Yes	Partly	No
19) *Opportunities for horizontal extensions of building*	Same for all	50 % ≥ Surplus space of site	30 % ≥ Surplus space of site	10 % ≥ Surplus space of site
20) *Extension or reuse of stairs and elevators*	Same for all	Yes	Partly	No

The tool automatically assigns points based on the input value to the indicator, as well as which criterion is met. If the input value meets the criteria for best transformation, the indicator is awarded 1 point, whereas 5 and 9 points respectively are awarded for medium and low transformation potential. If an input to an indicator is not inserted, it will be awarded 0 points and will not be included in the final transformation potential score. The 1 to 9 rating score corresponds to the SAVE framework and is chosen because it will increase potential operationality and implementation to relate to a system that is already a rating scale used in Danish municipalities.

4. Results from case studies of transformation potential.

The transformation potential tool has been tested on a case study of a building from Aalborg that was transformed from office space to student residence in 2020. The building was built in 2001 and was generally in a good technical condition. Despite being a relatively recent construction, the building was no longer in use and it was therefore necessary either to demolish or transform it. The tool developed in this paper was tested on the building conditions for the office building before the transformation. Figure 1 shows the results of the transformation potential score of the case study based on the twenty indicators in the transformation potential tool in this paper, followed by a test of 64 transformation indicators performed in collaboration with the authors of the paper on the same case study in Aalborg (Tram, 2020). The test of the 64 indicators could only be performed on a limited number of building types, and it was therefore only possible to assess the transformation potential for office, education and housing typologies. The result of the test of the tool with the twenty indicators and the testing of the 64 indicators showed that the building had the greatest potential to be transformed into an office. This was expected since the existing building is only about twenty years old and was therefore designed to meet the design criteria for present-day office buildings. The transformation potential for housing was the lowest of all the assessed building uses. Here, the application-specific indicators especially had a low transformation potential. In the test of the 64 indicators, the transformation potential for housing was significantly higher. At the same time, the transformation potential was generally slightly higher for all indicators when 64 indicators were assessed and not just 20.

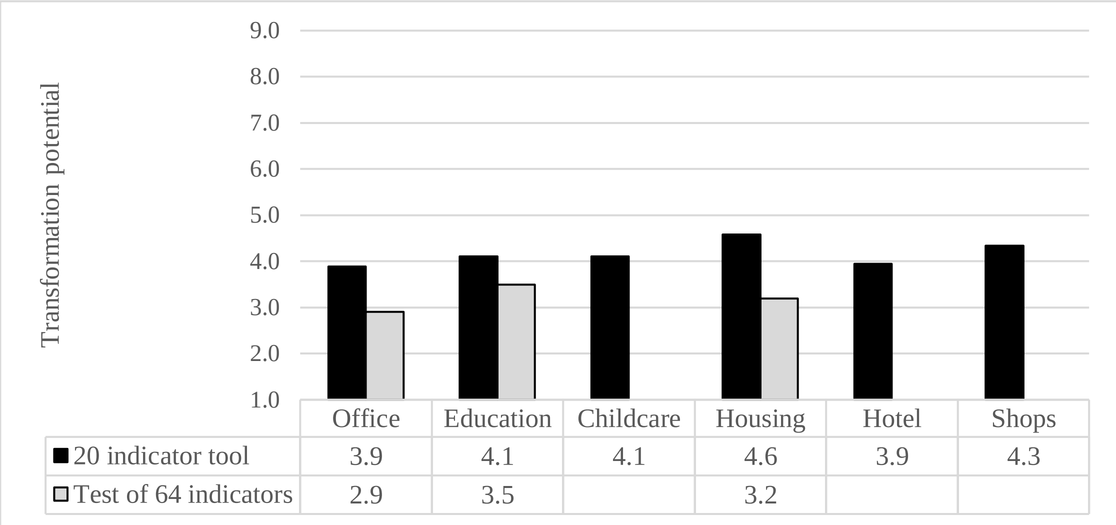

Figure 1. Results of transformation potential of the case study in Aalborg rated from 1-9 where 1 is the best value.

In this actual example, the office building was converted into student dormitories and housing in the form of small residential units. However, they are more reminiscent of a hotel than housing. The transformation potentials of 'Office' and 'Hotel' were close together, even though they differed in layout and features. Based on the result, this could therefore indicate that for the sample building, the design strategy with the most transformation potential was the one that was actually chosen. In the case study, the transformational potentials for the 'Education' and 'Childcare' typologies were closely related, though they should also meet the same criteria. These uses could therefore be combined in one typology.

5. Discussion

As mentioned in the literature study, several tools and many indicators already exist to assess transformation and flexibility, mainly concerning the design of new buildings. Adding criteria for several different building uses and typologies is an advantage in assessing the transformation potential of existing buildings. In addition, the purpose of the study was to test a simplified version with twenty indicators against a version where data is to be collected for 64 indicators. The background to selecting only twenty indicators was to establish a cost- and time-efficient tool to be used to scan several buildings in a large area and to identify buildings that are most suitable for the planned transformation strategy. The experience of the collection of data is that, although many of the indicators can be calculated using publicly available data in building registers, there are some indicators that require access to drawings or digital models of the building, a possible limitation in relation to the limited access to these. This can therefore complicate the ability to scan or screen a large area for its transformation potential. Since the differences between using the twenty most recognized indicators and a broader set of 64 indicators were quite small, it shows that it is possible to make a quick visualization of the transformation potential of buildings for use as a basis for decision-making in the early planning phases for both building owners and municipalities. As already mentioned, the SAVE value is relevant as an indicator because conservation values are one of the municipalities' most frequently used indicators for designating which buildings are to be demolished and which are to be preserved. This demonstrates a possible need for new methods to support municipal decision-making by evaluating both the historical qualities and the future potential qualities of buildings, such as usability and flexibility, especially for buildings without SAVE evaluations or with scores above 4. A tool for assessing and visualizing the transformation potential of existing buildings could be an additional criterion to attach to the SAVE method – a SAVE2.0. Future development of the tool might also involve stressing the urban-district level. For this purpose, an MCDM (multi-criteria decision-making) element, with its assessment of several indicators, could be combined with the TOPSIS method (Technique for Order of Preference by Similarity to Ideal Solution) for evaluating transformation strategies in an urban context. By assembling several buildings in the same framework, the tool can also assess the best transformation and renovation strategy for a defined urban area. A case study of a combined MCDM and TOPSIS framework (see Figure 2) could be used to evaluate the transformation potential of several buildings in an urban context and identify the buildings that will contribute the most value to the area if they are renovated, transformed (or demolished), as demonstrated by (Neel, 2020) in collaboration with the authors.

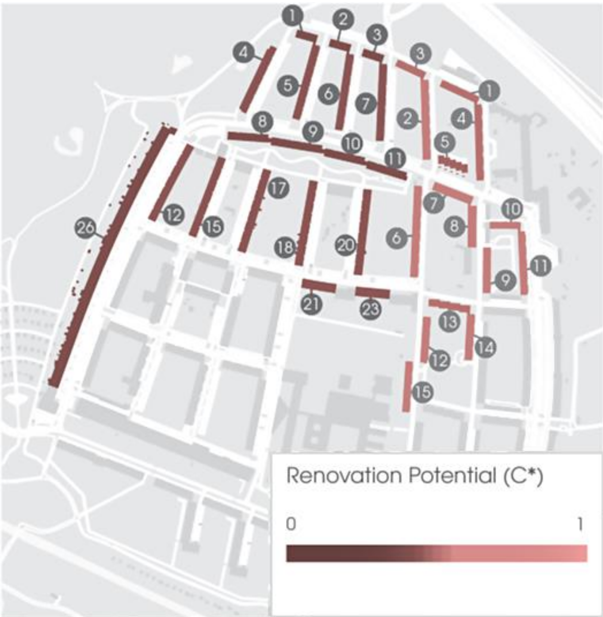

Figure 2. Visualization of renovation potential at urban level through indicators and MCDM+TOPSIS mapping rated from one to Zero (Neel, 2020). Zero means high potential for renovation.

In an MCDM development of the tool like that presented here, an ideal situation for sustainable urban development is for an area and the impact from the various indicators to be measured 'at a distance' from the ideal situation. However, if this is the case urbanity indicators will also need to be included, for example, social indicators, which are not directly related to transformations but are essential for the ideal urban situation. In that case, it is vital that data are easily accessible and, as far as possible, derived from publicly available information or already collected data on transformation.

6. Conclusion

Through literature reviews, case studies and collaboration with major architectural offices and authorities in Denmark, this project has defined and tested criteria and indicators that are relevant for evaluating buildings' transformation capacities and potentials. These indicators were tested using multiple-criteria decision-making models on various transformation and renovation projects at both urban and building scales. This showed that, by quantifying building capacity, it is possible to evaluate a project against several design strategies and thereby choose the transformation or renovation strategy that provides the best long-term sustainability. Developing the transformation framework further by visualizing the transformation strategies that provide the greatest flexibility concerning the environmental, economic and social indicators, and doing so continuously through planning and design, the framework allows buildings and urban areas to be designed with high future levels of transformability.

7. ACKNOWLEDGEMENTS

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Journal Paper 3

JP3: Environmental benefits of applying selective demolition to buildings: A case study of the reuse of façade steel cladding.

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Environmental benefits of applying selective demolition to buildings: A case study of the reuse of façade steel cladding

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A R T I C L E I N F O

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Building
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A B S T R A C T

This study presents a comparative life-cycle assessment (LCA) of two alternatives for the end-of-life handling of steel façade cladding from demolished buildings. The main objective is to investigate the environmental benefits of eighteen different environmental impact categories to indicate the respective potential impacts of the two demolition alternatives. We compare the selective demolition of façade cladding and the cladding's subsequent reuse with a conventional demolition scenario in which steel cladding is recycled as scrap. The study therefore expands the existing data foundation on selective demolition to support future decisions on the reuse of building components. The LCA was performed using parametric modeling to facilitate a thorough sensitivity and uncertainty analysis of the results. Results show that the environmental impact across all impact categories was generally lower for the selective scenario compared to the conventional demolition baseline scenario over the total evaluated life-cycle. However, we also see that the impacts related to the actual demolition process are higher for selective demolition due to the longer operating times of heavy machinery. This study contributes new knowledge on selective demolition processes, which can support decision-makers in choosing the most sustainable demolition practice. Through a comparison with the production of new products, it also becomes clear that there are environmental benefits to reusing components from demolition in connection with new constructions. Overall, this can help reduce the environmental impact of the construction sector.

1. Introduction

The building and construction sector is a significant contributor of waste, being responsible for 34% of all waste generated in OECD countries (Wilson et al., 2015). In addition, there is a demand for new materials for new construction and renovation, which means that the construction sector is responsible for 30% of global steel demand (UNEP, 2020) and that the global construction and infrastructure sectors together consume around 40% of all raw materials (Wit et al., 2018). The construction sector is important in reducing the impacts of emissions of greenhouse gasses and the use of resources since it is also responsible for 40% of all anthropogenic CO_2 emissions (UNEP, 2019). A way to reduce both CO_2 emissions from the production of new building products and the consumption of new materials is to recycle or reuse building materials and components from demolitions (Gaudillat et al., 2018). Previously, demolition waste typically resulted from low-cost demolition techniques, which often produced a crushed down inhomogeneous waste composition mainly suitable for earthworks and road construction (Tränkler et al., 1996). By separating demolition materials on site, it is possible to separate the waste into individual material fractions (Poon et al., 2001), thereby increasing the potential for materials recovery and recycling. On-site sorting, however, requires more space on the demolition site and more training of demolition workers in sorting materials into more fractions (Poon et al., 2001). Selective demolition differs from conventional demolition by focusing on recovering a larger share of materials and components for reuse, often by workers using light tools. This is in contrast to conventional demolition, which is dominated by heavy equipment used for crushing the materials, with little attention being paid to the recovery and recycling of the materials (Kourmpanis et al., 2008). Although many selective technologies and high-performing types of waste management have already been developed, a construction sector solidly based on traditional behavior and

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thinking, standard solutions and economic imperatives is one of the barriers to the greater implementation of selective demolition (Gálvez-Martos et al., 2018). Since selective demolition focuses on recovering materials and elements with the greatest value, the demolition process becomes more expensive, since it is labor-intensive and labor costs are high in some countries (Joint Research Center, 2012). A study of selective demolition in Lisbon concluded that landfill fees on mixed construction demolition waste would have to increase by up to 150% to make most selective demolitions economically competitive with conventional demolitions (Coelho and De Brito, 2011). However, selective demolition can also increase the number of materials that can be recycled, reducing waste treatment costs and providing an additional income from the economic value of the recovered materials (Cha et al., 2012). A study from Hong Kong showed that it was mainly high-value materials such as building installations, aluminum and copper that were deconstructed and recovered through on-site sorting, whereas materials such as concrete, plastics and timber were demolished conventionally due to their low market value (Poon et al., 2004).

The environmental impacts of the selective demolition process itself can exceed those related to the traditional demolition process due to the longer operating times needed for machinery and equipment (Ruggeri et al., 2019). However, selective demolition can also provide substantial environmental benefits compared to conventional demolition due to the potential for material recycling and reuse. This can avoid the extraction and production of new virgin materials and the impacts associated with virgin material production. Indeed, several life-cycle assessments (LCA) have been performed on construction and demolition (C&D) waste. Most focus on estimating the benefits of recycling materials compared to landfilling (Ortiz et al., 2010). Other LCAs have examined the environmental impacts of selective demolition, but their focus has been on the recovery and recycling of materials rather than the potential of recovered building components for reuse (Di Maria et al., 2018; Pantini and Rigamonti, 2020).

Indeed, these studies reveal the larger environmental impacts of selective demolition due the greater level of operating machinery, as well as the benefits of the recycling, which outweigh the direct impacts of the demolition process itself (Di Maria et al., 2018). Moreover, the environmental impacts of the selective demolition process can be reduced by switching from diesel-powered to electric-powered machinery (Pantini and Rigamonti, 2020). A few studies have examined the environmental impact and economic benefits of the adaptive reuse of buildings. However, these studies mainly deal with a partly selective disassembly of building components (Sanchez et al., 2020) or the construction of new buildings from reused products (De Wolf et al., 2020; Minunno et al., 2020). Indeed, studies looking into the impacts of recovering building components with a view to reusing them as components, compared to conventional treatment and recycling of the materials for other purposes are generally lacking. However, an LCA case study of selective demolition with subsequent reuse of structural steel has shown that reuse can provide savings of 1870 kg CO_2 equivalents per ton of reused steel compared to typical recycling of structural steel (Yeung et al., 2017). As far as the authors of this study are aware, no detailed LCA studies exist of the selective demolition of steel façade cladding with subsequent preparation for reuse as cladding.

Thus, the goal of this study is to investigate the environmental benefits of using selective demolition for façade cladding rather than conventional demolition. This will be evaluated using a comparative LCA of the two approaches to the demolition of steel façade cladding and the treatment of waste materials by either recycling or preparation for reuse. A secondary objective is to collect and present additional data on the selective demolition of façade cladding to expand existing data on workflows in selective demolition. The objective is to inform building developers, demolition companies and researchers about the environmental benefits of choosing selective demolition over conventional demolition. The paper will also contribute knowledge and data to further develop and support future LCA studies on selective demolition and the circular reuse of building components.

2. Methodology

2.1. Description of demolition case study

The demolition that is the focus of this study was carried out in Denmark in 2020. The demolition case study consists of a school site built in various construction periods from 1937 to 1967. The building from the site used in this case study was built in 1967 and consisted of exterior walls in concrete with steel cladding, floor decks of reinforced concrete and bitumen roofing. In the selective demolition of the building, it has mainly been possible to reuse the façade cladding, as well as a few internal installations. The remaining building was demolished conventionally for recycling by crushing the concrete and burning wood to produce energy. The steel cladding was selectively removed before the conventional demolition of the rest of the building.

2.2. Life-cycle assessment

2.2.1. Functional unit

In relation to LCA, the functional unit (FU) is a framed definition of the system's function, which makes it possible to compare the two systems in this study, or possibly, to compare our results with LCA results from other studies. The FU in this study is defined as *"Demolition and waste treatment of 1m^2 façade cladding in Denmark in 2020"*. The system will be modelled such that all processes concerning preparation for reuse will be regarded as waste treatment, as the processes for this preparation are an extension of the demolition. The year 2020 has been chosen, as it is the year in which the case study of the selective demolition was carried out, as well as forming the background for the baseline scenario in the case of the conventional demolition, which must be expected to change over time.

2.2.2. System boundaries

To investigate the differences between selective and conventional demolition, two scenarios (see Fig. 1) were modeled. System 1) is a baseline scenario, which consists of conventional demolition followed by waste treatment with recycling of the steel façade cladding from the demolition, together with the production of new cladding to compensate for material losses during waste treatment. System 2) is a reuse scenario with selective demolition, followed by preparation for reuse of the steel cladding that is slated for reuse, together with preparation for the recycling of damaged cladding and the production of new cladding to compensate for material losses. System equivalence to the (European Committee for Standardization, 2011) was achieved by expanding the system to ensure equivalence in the functions provided by the two systems. The production of new cladding to compensate for losses is included in both scenarios to ensure that the functions in the two systems are equivalent in both scenarios, that is, that a 1 m^2 façade is demolished and a 1 m^2 façade is produced in the two systems. The different stages in the two systems are divided according to the building life-cycle classifications set out in the EN 15,978: 2011 standard (European Committee for Standardization, 2011). This classification system is used to divide the processes into a building's lifetime by classifying each process with a letter and a number. This study deals only with A1–3 production processes (raw materials supply, transport, manufacturing) and C1–4 end-of-life processes (demolition, transport, waste processing, disposal).

As this study focuses on the differences between conventional and selective demolition, the foreground system for conventional demolition (see Fig. 2) only contains the following waste-related processes: C1 deconstruction, C2 transport of waste and C3 waste-processing according to the process definition in (European Committee for Standardization, 2011). In addition, the production of new steel cladding (See Fig. 4) to make 1 m^2 façade cladding available after the demolition is also

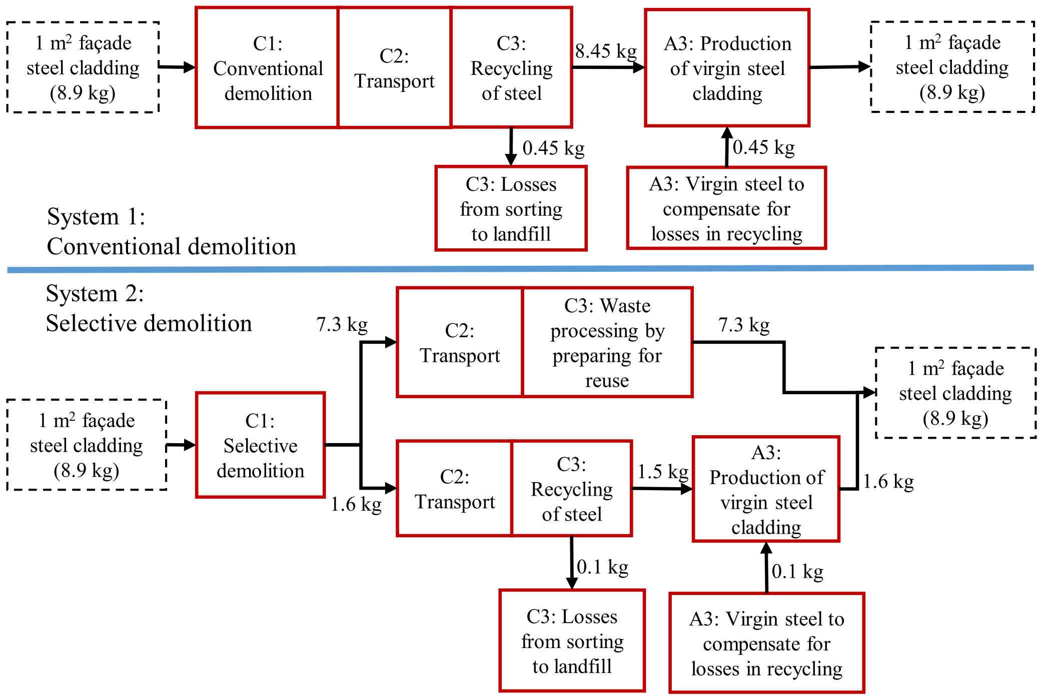

Fig. 1. Principles of the two demolition scenarios covered by this study. System expansion has been used to ensure that the functions provided by the two assessed systems is equivalent.

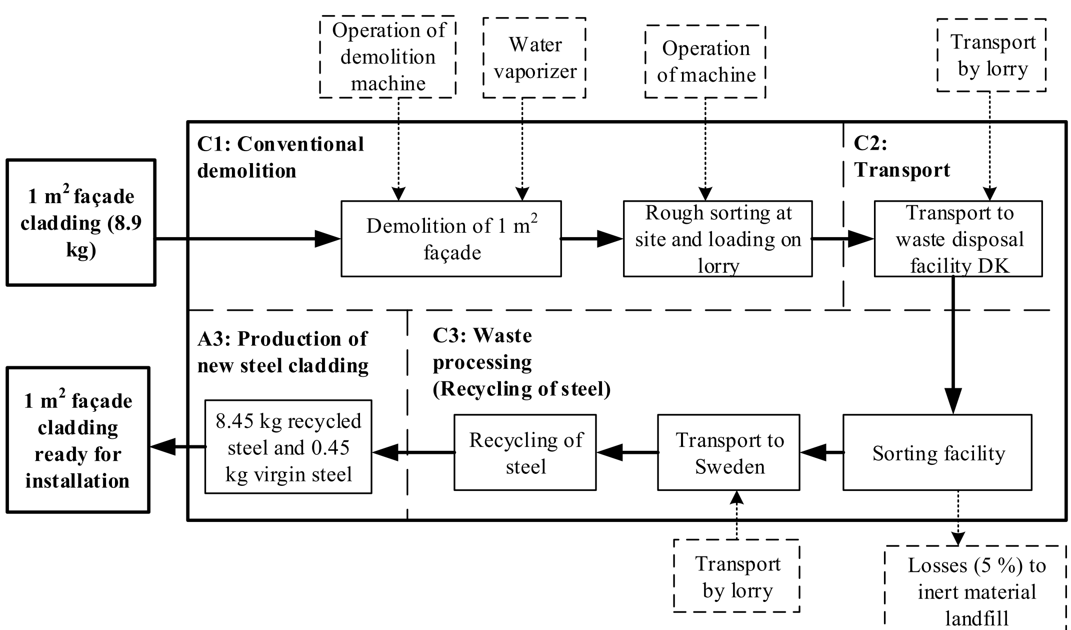

Fig. 2. Boundaries and flows for the conventional demolition scenario, with recycling of the steel façade, as well as the production of new steel façade cladding.

included in the foreground system.

The system for the selective demolition scenario is more comprehensive (see Fig. 4) since the selective scenario also contains the following building life processes: C2 (waste transport), C3 (waste processing) and A3 (manufacturing) from the conventional system, as some cladding plates will be damaged during selective demolition. The foreground system in the selective scenario also includes C1 (selective demolition), C2 (transport for reuse) and C3 (waste processing of the old steel cladding) as preparation for its reuse.

To ensure that the function in both scenarios was the same, it was assumed that each system should be able to supply 1 m^2 of façade cladding. In the selective scenario, the recycling of existing façade panels could provide an output of 0.82 m^2 of façade cladding, leaving 0.18 m^2 to be provided through the production of new façade cladding. In the conventional scenario, it was necessary to cover the entire need for 1 m^2 of façade cladding through the production of new steel cladding. The process for the production of new steel façade cladding shown in Fig. 3 is based on the requirement for 5% virgin steel and 95% recycled steel in the conventional scenario.

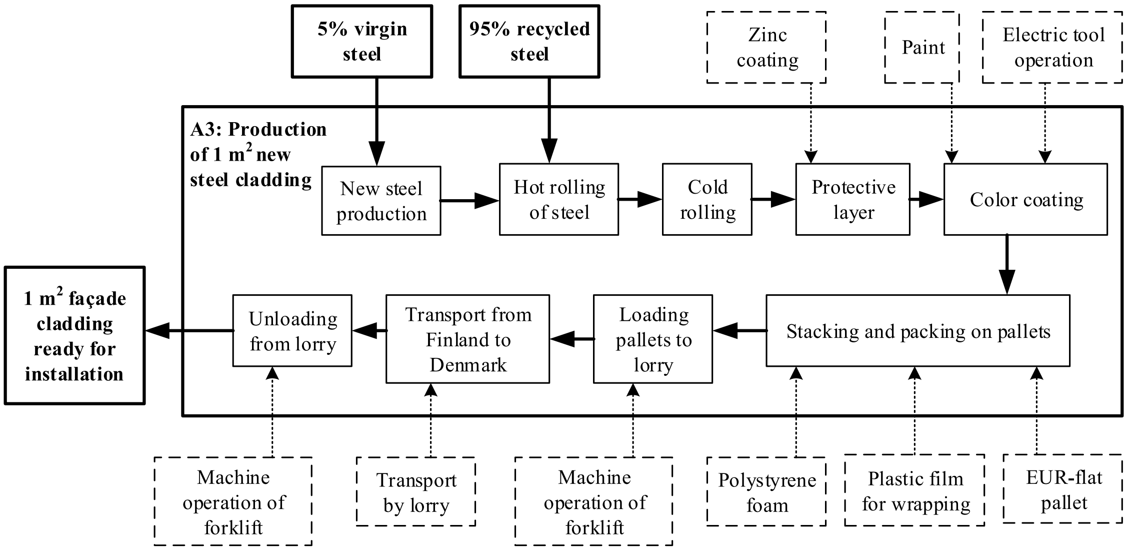

Fig. 3. Boundaries and flows for the production of 1 m^2 new steel façade cladding.

2.3. Life-cycle inventory

Data on the demolition process is provided by the demolition company involved in the case study. The workflows, machine specifications, time consumption and materials used in the demolition process in the selective scenario are based on data from this actual case of demolition. The data for the demolition process in the conventional scenario is based on a typical demolition delivered by the same demolition company.

The façade cladding consists of gray-coated steel panels with a width of 1520 mm and a height of 620 mm (0.94 m^2) and 1 mm thickness. In addition, there is a 30 mm wide bent profile 25 mm from the edge all the way around one plate (0.13 m^2), which means that the total surface area of a façade panel is 2.14 m^2. Each façade panel weighs 8.4 kg, equivalent to 8.9 kg per FU.

2.3.1. Selective demolition process

The façade cladding is taken down by removing the old screws. This is done with a Milwaukee M18 onePD2 - 18 W electric screwdriver. An angle grinder (Bosch GWS7–125 - 720 W) was sometimes needed to cut the screws if they were broken. This can have a major impact on the reusability of the façade cladding, as the angle grinder can damage the panels. The share of façade cladding that cannot be reused as façade cladding and must be recycled as steel therefore depends on how many panels are removed using destructive methods, such as the angle grinder. In the case study, it was possible to reuse 535 façade panels out of the total number of 630 removed. This means that there was a loss of 18% in the selective demolition process. This quantity was not suitable for reusing and therefore had to be handled as scrap steel for recycling. Façade cladding high up on the building was not accessible from the ground level and required a Manitou MRT2540P+ telescopic handler (See Fig. 5). This was also used to lower the façade cladding once it had been removed.

The façade cladding was then stacked on pallets with 32 façade panels on each pallet. A forklift transported the pallets from the dismantling site to the sorting area, where damaged cladding was removed and façade cladding suitable for reuse was packed on EUR-pallets with 20 cladding plates per pallet. The total time spent per square meter of dismantled façade cladding was on average 17 min, based on data from this demolition case. No time consumption was recorded for the separate processes in the selective demolition. On-site transport of façade cladding from the dismantling site to the sorting area, as well as the subsequent loading of packed pallets onto the lorry, is by forklift (Giant 452 T). Based on the workflows, it has been assumed that 0.5 min of the 17 min per façade cladding plate are consumed by the forklift operations. The remaining 16.50 min, based on the description of the handling of the plates, are assumed to be divided equally between the dismantling process with the telescopic handler and the sorting and packing process where machinery is not used.

2.3.2. Conventional demolition process

The modeling of a conventional demolition process is based on a typical demolition with data provided by the demolition company. The main machinery used in this process is a demolition machine equipped with a water vaporizer to reduce dust. The water vaporizer uses 40 liters of water per minute and has a power output of 750 W. The demolition machine can demolish 50 m^2 buildings during a seven-hour workday. This is equivalent to 7.14 m^2 buildings per hour or 8.4 min per m^2. Here, it is assumed that a 1 m^2 façade system takes the same amount of time to demolish as a 1 m^2 building floor area. The steel cladding makes up only 7.5% of the façade system in the reference system, which means that it takes 37.8 s to demolish one FU using the conventional demolition process. In addition, it is assumed that 30 s of machine operations per FU are subsequently spent on the site for rough sorting and loading the steel scrap onto a lorry.

2.3.3. Recycling of steel

Damaged façade cladding for recycling is transported 30 km away for sorting. A recycling rate of 95% was modeled for the steel (Gaudillat et al., 2018), as 5% is modelled as lost during sorting. The loss is sent to an inert material landfill. In Sweden, steel recycling takes place about 750 km from the sorting site. The steel scrap is recycled into secondary steel in an electric arc furnace.

2.3.4. Production of new façade cladding

The production of new façade cladding is based on descriptions from an Environmental Product Declaration (EPD) for GreenCoat façade panels (EPD International, 2020). All the processes modeled in the production of new façade cladding are depicted in Fig. 4, and the linked ecoinvent processes and units are listed in Supplementary Material (SM) Table S1. The steel input to the production of new façade cladding consists of 95% recycled steel and 5% virgin steel. The production of virgin steel uses a basic oxygen furnace, which produces primary steel without scrap input. The steel is first hot-rolled and then cold-rolled to obtain the right steel thickness of 1 mm. A zinc-coated layer is added to the cladding to improve weather resistance. According to the EPD for GreenCoat façade cladding, zinc degrees of protection from Z100 to

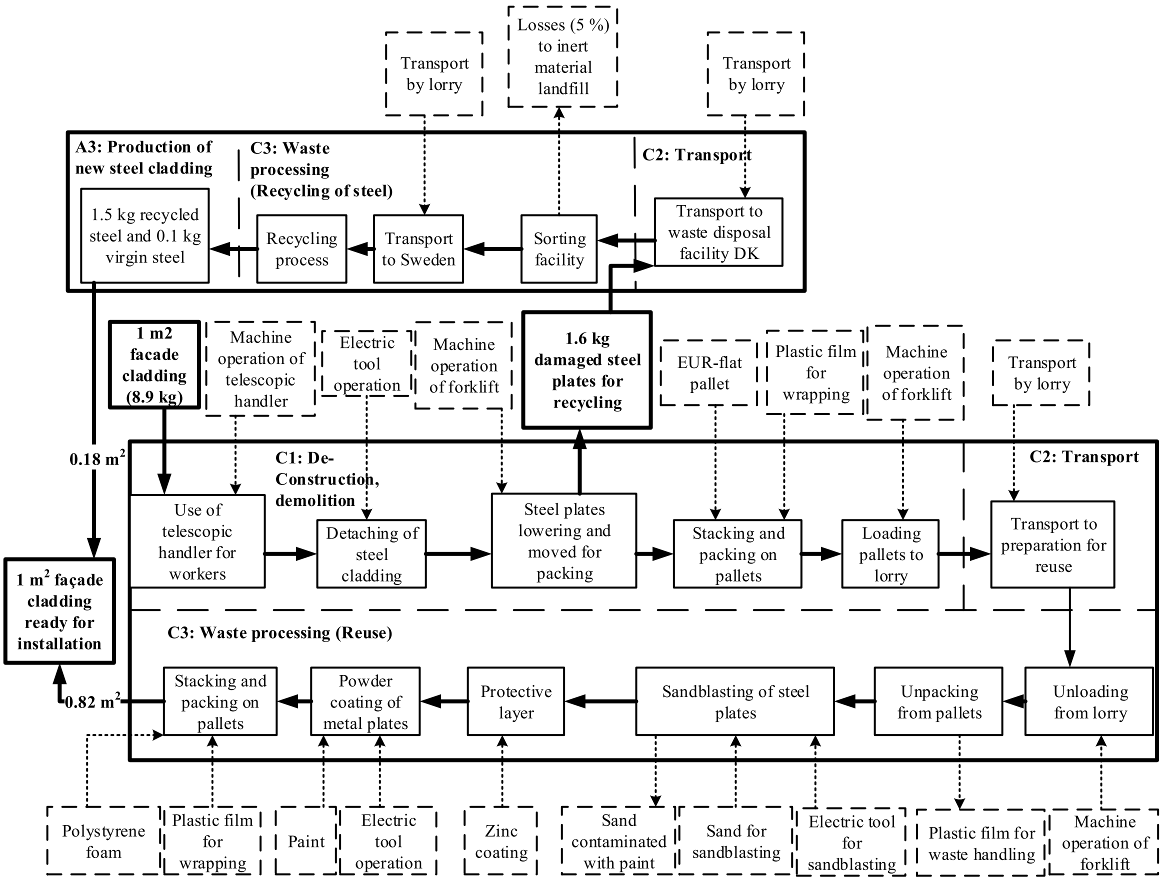

Fig. 4. System boundaries and flows for the selective demolition scenario with the dismantling of steel cladding, transport, preparation for reuse with sandblasting and painting, recycling of the damaged steel cladding, and production of new cladding to compensate for losses.

Fig. 5. Manual dismantling of the steel cladding with telescopic handler during the selective demolition process in the case study.

Z350 are used in the production of façade cladding. The amount of zinc will determine how weather-resistant the façade panels are. In this study, it is assumed that Z275 protection will be used (same as listed in the EPD), which gives a zinc thickness of 20 μm. The thickness of the color coating is 12 μm on the back of the façade cladding and can vary from 25 μm to 50 μm on the front according to the EPD. It is therefore assumed that the thickness of the paint coating on the front is 37.5 μm. After being painted, the façade cladding is stacked on wooden EUR pallets. Slabs of polystyrene foam are added between each panel for protection, and the entire pallet stacked with twenty cladding units is wrapped in three layers of thin plastic film. The façade cladding is produced in Finland, so transporting the packed façade cladding 1200 km to Denmark by lorry is included in the process.

2.3.5. *Preparation for reuse*

'Preparation for reuse' denotes the process where old façade cladding units are treated so they can be reused on equal terms as new façade cladding. The main elements are that the façade cladding must be cleaned through sandblasting and repainting. The old façade cladding units are received in the same form as when they were packed on pallets at the demolition site. The transport distance from the demolition site is assumed to be around 30 km, thus covering most of the Copenhagen area. After panels are unloaded from the lorry and plastic film is removed from the pallets, the panels are moved to a sandblasting cabinet and sandblasted individually. The sandblasting process had to be created as it was not present in the ecoinvent database. The resulting process relies on inputs of silica sand and electric tool operation. The output of the sandblasting process is removed waste paint and the used silica sand, which go to sanitary landfill. After sandblasting, a protective layer must be added to the now untreated steel cladding. Here, several different types of protection could be used, the simplest of which could be a basic primer with subsequent main paint coating. The reused façade cladding was assumed to be given the same zinc coating and painting as new façade cladding (see Section 2.3.4) to guarantee that the reused façade cladding has weather resistance and a sufficient lifetime. Finally, the façade cladding is stacked on pallets, it being assumed that the pallets from the delivery of the cladding can be re-used. Slabs of polystyrene foam are added between each panel for protection. Finally, the entire pallet with twenty stacked cladding panels is wrapped in three layers of thin plastic film, making it ready for transportation to a retailer or construction site. However, this transport falls outside the scope of this LCA study, since preparation is already being carried out in the Copenhagen area.

2.4. Sensitivity and uncertainty analysis

To investigate how sensitive the LCA results are to changes in input parameters, a sensitivity analysis was performed by calculating normalized sensitivity coefficients (Eq. (1)) (Ryberg et al., 2015) for all input parameters, with each parameter being perturbed with a 10% increase.

$$S_{coef} = \frac{\frac{\Delta IS}{IS_0}}{\frac{\Delta a_k}{a_{k,0}}} \quad (1)$$

Where IS_0 is the initial impact score, ΔIS is difference between the impact score based on the perturbed parameter value, and the initial impact score $a_{k,0}$ is the original parameter value, Δa_k is difference between the perturbed parameter value and original parameter value.

Monte Carlo simulation was used to propagate uncertainty of the background ecoinvent processes and of the input parameters to indicate overall uncertainty of the LCA result. The Monte Carlo simulation was done with 10,000 iterations, and the uncertainty of all input parameters was assessed individually and is described in SM Table S2. Based on the Monte Carlo simulation, a non-parametric Mann-Whitney *U* test was conducted to test for significant differences between the impacts scores of the two demolition alternatives. We tested for statistically significant difference with $\alpha = 0.05$, the results of the *U* test being given in SM Table S3.

3. Results and discussion

3.1. Comparison of conventional and selective demolition

Fig. 6 shows large environmental benefits from using the principles of selective demolition as opposed to conventional demolition. Environmental impacts are lowest for the selective scenario for all impact categories, which means that the selective demolition of steel façade is better than with conventional demolition. The impact category with the largest difference in impacts between the two scenarios was human carcinogenic toxicity, where the impacts were 77% lower in the selective than in the conventional scenario. However, there was almost no difference between the two scenarios for the 'land-use' impact category, where virtually all the impact came from the EUR-pallets, and the 'mineral resource scarcity' category, where the impacts came especially from the zinc protection. In relation to human carcinogenic toxicity, the large impact in the conventional scenario was due to the recycling process of steel. The impact category with the second most difference between the two scenarios was 'ionizing radiation', where the impact was 59% lower than in the conventional scenario. Here again, it was the recycling of steel which had a greater impact in the conventional scenario, but the cold- and hot-rolling in the production of new sheets also had a high contribution and were responsible for the majority of the difference for the impact categories 'water consumption' and 'freshwater eutrophication', where the difference was also over 50% between the two scenarios.

Compared to 'global warming', in the selective scenario there was a saving in the CO_2-related impact of 44% compared to the conventional scenario. Here, the impact in the production of new cladding in the conventional scenario and of the recycling of steel was more than twice as large as the impact from preparing old sheets for reuse. In addition, there were more CO_2 emissions related to transport in the conventional scenario, which is also responsible for some of the difference between the two scenarios. However, in the selective demolition process itself, the global warming impacts were 20% higher than in the conventional demolition process. This is mainly because there was more machine operation with selective demolition.

The demolition machine in the conventional scenario could demolish much faster than the manual selective demolition, where machinery nonetheless still had to be used. This meant that the environmental impact in the selective demolition process was greater than in the conventional demolition process because of the increased diesel consumption, which was also found by Di Maria et al. (2018). When, in selective demolition, the proportion of building parts that are not suitable for reuse increases, the environmental impact of the entire selective scenario will move closer to the conventional baseline scenario because more is recycled and more production of new cladding is needed. In

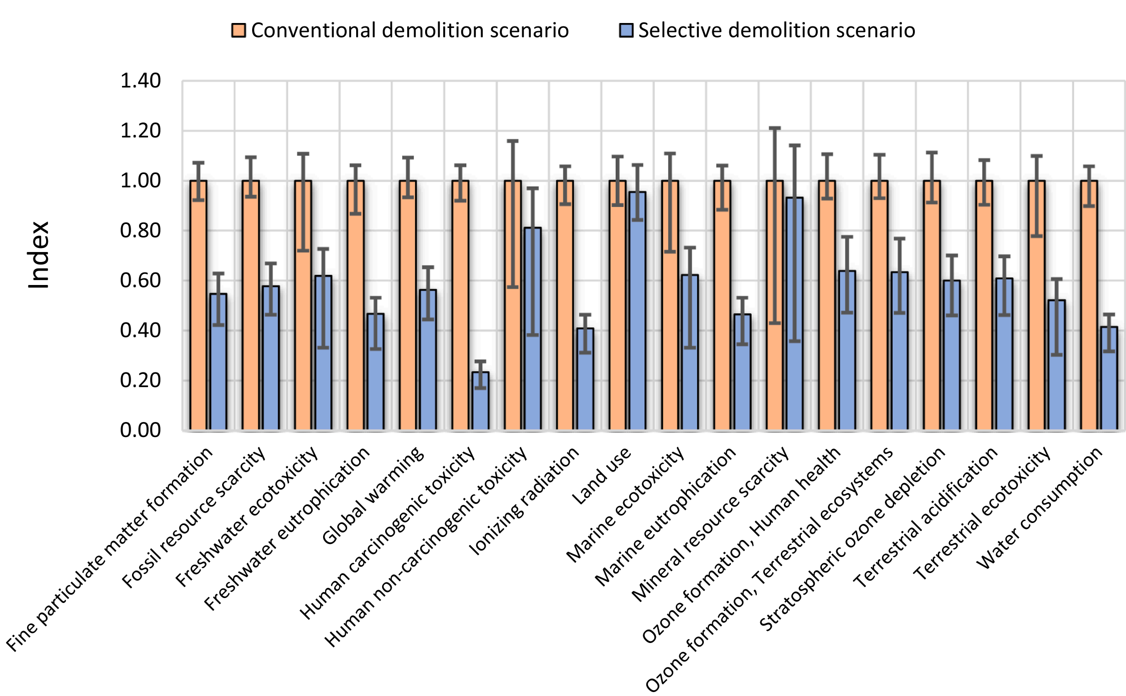

Fig. 6. Comparison of the impact scores on index level for the selective demolition scenario and the conventional demolition scenario respectively.

relation to the loss, it is therefore important that the dismantling takes place as gently as possible. It is also possible that smaller or larger dimensions of façade claddings or their location on the building will have an impact on the time consumption and machinery that must be used to dismantle the cladding.

The results show that the environmental impact in many of the categories was highly dependent on the zinc protection. If the system were to be developed further, it might therefore be relevant to investigate in more detail exactly how much zinc protection is needed. The primary purpose of this study is to investigate the consequence of the selective demolition, and therefore the façade cladding is not studied throughout its whole lifetime. The zinc protection will have an impact on the durability of the façade cladding and how long a lifetime they can be guaranteed due to the protective zinc's self-healing properties in closing up minor scratches on the surface. It could also be relevant to investigate further whether zinc protection is indeed necessary and whether other alternatives to zinc can be used to reduce the environmental impact. In this study, zinc protection was chosen to be certain that the reused cladding was a genuine alternative to newly produced cladding. This is especially important to ensure the same assumptions in both scenarios when the LCA study does not examine the material over the entire lifetime of the cladding. At the same time, zinc coating is also the most widely used form of protection for steel elements in façade systems (Soufeiani et al., 2020), making it a realistic choice for comparing the two scenarios. The uncertainty in the results is shown as the 95% confidence interval in Fig. 6. In general, there seems to be a substantial difference in the impact scores for the conventional and the selective demolition scenarios. Only for the categories 'freshwater ecotoxicity', 'human non-carcinogenic toxicity', 'land use', 'marine ecotoxicity' and 'mineral resource scarcity' do we see overlapping confidence intervals. This is underlined by the *U* test, which shows that there is a significant difference in impact scores across all impact categories for the two demolition alternatives (see SM Table S03). The uncertainty is greatest for the impact categories 'human non-carcinogenic toxicity', 'mineral resource scarcity' and 'marine ecotoxicity', where zinc protection accounts for the majority of the uncertainty. In relation to zinc protection, the uncertainty was such that variations between Z100 protection and Z350 protection could be detected. Z275 protection with a zinc thickness of 20 μm was used in the calculation. The uncertainty here therefore shows what the impact might have been if another form of zinc protection had been used. The impact could therefore have been reduced by an additional 60% compared to 'mineral resource scarcity' if Z100 protection had been chosen instead. However, this does not affect the comparison between the two scenarios since the same degree of protection should have been used in both scenarios to guarantee the same lifetimes for the products and thereby ensure that they were genuinely comparable alternatives.

The sensitivity analysis (See SM Tables S4, S5) showed that the results were very sensitive in relation to a few parameters, whereas the majority of the parameters had very little sensitivity. In the conventional scenario, it was especially the weight of the façade cladding that was very sensitive in relation to the impact results. The amount of zinc protection was the parameter that had the second greatest sensitivity. In addition, the number of façade panels on a EUR pallet showed a large negative sensitivity in relation to the 'land-use impact' category.

3.2. Life-cycle stage contribution for the conventional demolition scenario

The impact results from of the conventional demolition scenario (See Table 1) show that the production process of new façade cladding was responsible for the majority of the total impact in almost all categories. Especially the zinc protection accounted for most of the impacts. Indeed, zinc protection accounted for up to 90% of the impact of the entire scenario for the impact category mineral resource scarcity. For most other impact categories, the majority of the impact was divided among the four processes of zinc protection, steel recycling, sheet rolling and color coating. However, the 'land-use' impact category was dominated by the EUR-pallets used in production of new cladding, which contributed 76% of the total impact in the conventional scenario. In general, transport of cladding from demolition to waste processing by sorting accounted for a very small share of the total impact with less than 0.3% contribution across all impact categories. However, transport from

Table 1
Characterized results for the conventional demolition scenario. Results are shown per life-cycle stage and in terms of total impact across the total evaluated life-cycle.

Impact category	Unit	C1: Demolition	C2: Transport (Recycling)	C3: Waste processing (Recycling)	A3: Production of new façade cladding 1 m^2	Total impact for conventional scenario
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.78×10^{-3}	4.86×10^{-5}	9.19×10^{-3}	2.04×10^{-2}	$\mathbf{3.24 \times 10^{-2}}$
Fossil resource scarcity	kg oil eq	8.82×10^{-1}	1.53×10^{-2}	$1.60 \times 10^{+0}$	$4.34 \times 10^{+0}$	$\mathbf{6.83 \times 10^{+0}}$
Freshwater ecotoxicity	kg 1,4-DCB	1.90×10^{-2}	1.02×10^{-3}	6.31×10^{-1}	$2.00 \times 10^{+0}$	$\mathbf{2.65 \times 10^{+0}}$
Freshwater eutrophication	kg P eq	1.10×10^{-4}	3.26×10^{-6}	2.52×10^{-3}	6.29×10^{-3}	$\mathbf{8.92 \times 10^{-3}}$
Global warming	kg CO_2 eq	$2.80 \times 10^{+0}$	4.44×10^{-2}	$4.91 \times 10^{+0}$	$1.37 \times 10^{+1}$	$\mathbf{2.15 \times 10^{+1}}$
Human carcinogenic toxicity	kg 1,4-DCB	5.73×10^{-2}	9.20×10^{-4}	$1.62 \times 10^{+1}$	$4.36 \times 10^{+0}$	$\mathbf{2.06 \times 10^{+1}}$
Human non-carcinogenic toxicity	kg 1,4-DCB	2.94×10^{-1}	2.59×10^{-2}	$8.92 \times 10^{+0}$	$4.79 \times 10^{+1}$	$\mathbf{5.72 \times 10^{+1}}$
Ionizing radiation	kBq Co-60 eq	3.45×10^{-2}	1.03×10^{-3}	9.61×10^{-1}	$1.47 \times 10^{+0}$	$\mathbf{2.46 \times 10^{+0}}$
Land use	m^2a crop eq	6.93×10^{-3}	1.89×10^{-3}	1.85×10^{-1}	$2.23 \times 10^{+0}$	$\mathbf{2.42 \times 10^{+0}}$
Marine ecotoxicity	kg 1,4-DCB	2.69×10^{-2}	1.62×10^{-3}	9.12×10^{-1}	$2.72 \times 10^{+0}$	$\mathbf{3.66 \times 10^{+0}}$
Marine eutrophication	kg N eq	9.07×10^{-6}	2.72×10^{-7}	1.50×10^{-4}	4.30×10^{-4}	$\mathbf{5.89 \times 10^{-4}}$
Mineral resource scarcity	kg Cu eq	4.76×10^{-3}	1.70×10^{-4}	1.67×10^{-2}	$2.32 \times 10^{+0}$	$\mathbf{2.34 \times 10^{+0}}$
Ozone formation, human health	kg NO_x eq	1.15×10^{-2}	1.40×10^{-4}	2.01×10^{-2}	3.62×10^{-2}	$\mathbf{6.79 \times 10^{-2}}$
Ozone formation, terrestrial ecosystems	kg NO_x eq	1.17×10^{-2}	1.50×10^{-4}	2.05×10^{-2}	3.83×10^{-2}	$\mathbf{7.06 \times 10^{-2}}$
Stratospheric ozone depletion	kg CFC11 eq	1.65×10^{-6}	3.35×10^{-8}	2.71×10^{-6}	7.06×10^{-6}	$\mathbf{1.14 \times 10^{-5}}$
Terrestrial acidification	kg SO_2 eq	6.90×10^{-3}	1.10×10^{-4}	1.86×10^{-2}	4.48×10^{-2}	$\mathbf{7.03 \times 10^{-2}}$
Terrestrial ecotoxicity	kg 1,4-DCB	$3.24 \times 10^{+0}$	6.03×10^{-1}	$8.55 \times 10^{+1}$	$1.21 \times 10^{+2}$	$\mathbf{2.10 \times 10^{+2}}$
Water consumption	m^3	2.73×10^{-2}	7.07×10^{-5}	7.01×10^{-2}	2.42×10^{-1}	$\mathbf{3.40 \times 10^{-1}}$

sorting to recycling in Sweden had greater contribution due to the long distance involved of 750 km, which meant that 5% of the CO_2 emissions for the entire scenario came from this transportation. Transport of new façade panels from Finland to Denmark was another major CO_2 contributor, responsible for 10% of the scenario's total CO_2-related emissions. Overall, 15% of the total global warming impact in the conventional scenario can be related to transport.

In the conventional demolition process, there was a very large difference in how much the different impact categories contributed to the overall impacts for the whole scenario. Several of the toxicity-related impact categories contributed less than 1% of the total impact in the system, whereas the ozone-related impact categories contributed more than 15% of the total impacts, and for global warming, the conventional demolition was also a major contributor, with 13% of the total impact throughout the scenario being due to the operation of the demolition machine. Although a water vaporizer was used in the conventional demolition scenario to avoid the spreading of dust, which is not necessary in the case of selective demolition, the impacts of the amounts of water consumed by the water vaporizer in the conventional demolition scenario only accounted for 7.5% of the total impacts in the water consumption category in that scenario.

3.3. Life-cycle stage contribution for the selective demolition scenario

In the selective scenario, there was an input of 0.18 m^2 of new cladding, corresponding to 18% of one FU, but for most impact categories the production of new façade cladding accounted for between 18% and 30% of the total impacts. However, there were exceptions for the categories 'human toxicity', 'ozone formation' and 'land use', where impacts for the production of new cladding accounted for 15% to 17% of total emissions. For 'human carcinogenic toxicity', the majority of the impact was in steel recycling, although the amount of steel was only 18% of the total amount, whereas the majority of the impact in 'human non-carcinogenic toxicity' occurred in connection with preparation for reuse and was related to the zinc treatment of the reused façade cladding. In relation to the impact from land use, most of it was due to the use of EUR-pallets. Again, the impact of the transport from demolition to waste processing was very small (see Table 2), mostly below 0.2%.

In preparation for reuse, the zinc protection was responsible for a large share of the impacts, as with the production of new façade cladding, followed by the impacts of powder coating as the second largest contributor. However, silica sand was responsible for 57% of the total impact on land use in this process. Also, powder coating was responsible for the largest share of global warming impacts in preparation for reuse, corresponding to 36% of the impacts. This was followed by zinc coating (28%), silica sand (17%) and polystyrene foam slabs (15%). The disposal of silica sand and waste paint from sandblasting had only minor impacts, mainly below 5% of the total impacts in the process.

In the selective demolition process, was there considerable differences in how much the different impact categories contributed to the total impact for the scenario. Here it was especially land use that is indicated, as there was a large impact from the EUR-pallet, which was used to transport the cladding around the demolition site and subsequently to the site where the cladding would be prepared for reuse. In addition, there was also a large contribution to the overall impact of the scenario in relation to fine 'particulate matter formation', 'fossil

Table 2
Characterized results for the selective demolition scenario. Results are shown per life-cycle stage and as total impact across the total evaluated life-cycle.

Impact category	Unit	C1: Demolition	C2: Transport (Reuse)	C2: Transport (Recycling)	C3: Waste processing (Reuse)	C3: Waste processing (Recycling)	A3: Production of new façade cladding 0.18 m^2	Total impact for selective scenario
Fine particulate matter formation	kg $PM_{2.5}$ eq	4.40×10^{-3}	4.55×10^{-5}	8.74×10^{-6}	7.97×10^{-3}	1.65×10^{-3}	3.67×10^{-3}	$\mathbf{1.77 \times 10^{-2}}$
Fossil resource scarcity	kg oil eq	$1.09 \times 10^{+0}$	1.43×10^{-2}	2.75×10^{-3}	$1.77 \times 10^{+0}$	2.87×10^{-1}	7.81×10^{-1}	$\mathbf{3.94 \times 10^{+0}}$
Freshwater ecotoxicity	kg 1,4-DCB	3.78×10^{-2}	9.50×10^{-4}	1.80×10^{-4}	$1.13 \times 10^{+0}$	1.14×10^{-1}	3.60×10^{-1}	$\mathbf{1.64 \times 10^{+0}}$
Freshwater eutrophication	kg P eq	2.30×10^{-4}	3.05×10^{-6}	5.87×10^{-7}	2.36×10^{-3}	4.50×10^{-4}	1.13×10^{-3}	$\mathbf{4.17 \times 10^{-3}}$
Global warming	kg CO_2 eq	$3.36 \times 10^{+0}$	4.15×10^{-2}	7.99×10^{-3}	$5.33 \times 10^{+0}$	8.84×10^{-1}	$2.47 \times 10^{+0}$	$\mathbf{1.21 \times 10^{+1}}$
Human carcinogenic toxicity	kg 1,4-DCB	8.81×10^{-2}	8.60×10^{-4}	1.60×10^{-4}	$1.03 \times 10^{+0}$	$2.91 \times 10^{+0}$	7.85×10^{-1}	$\mathbf{4.81 \times 10^{+0}}$
Human non-carcinogenic toxicity	kg 1,4-DCB	6.08×10^{-1}	2.43×10^{-2}	4.67×10^{-3}	$3.56 \times 10^{+1}$	$1.61 \times 10^{+0}$	$8.63 \times 10^{+0}$	$\mathbf{4.64 \times 10^{+1}}$
Ionizing radiation	kBq Co-60 eq	5.75×10^{-2}	9.60×10^{-4}	1.80×10^{-4}	5.13×10^{-1}	1.73×10^{-1}	2.64×10^{-1}	$\mathbf{1.01 \times 10^{+0}}$
Land use	m^2a crop eq	$1.53 \times 10^{+0}$	1.77×10^{-3}	3.40×10^{-4}	3.49×10^{-1}	3.33×10^{-2}	4.02×10^{-1}	$\mathbf{2.31 \times 10^{+0}}$
Marine ecotoxicity	kg 1,4-DCB	5.19×10^{-2}	1.52×10^{-3}	2.90×10^{-4}	$1.57 \times 10^{+0}$	1.64×10^{-1}	4.89×10^{-1}	$\mathbf{2.28 \times 10^{+0}}$
Marine eutrophication	kg N eq	1.91×10^{-5}	2.55×10^{-7}	4.89×10^{-8}	1.50×10^{-4}	2.79×10^{-5}	7.66×10^{-5}	$\mathbf{2.74 \times 10^{-4}}$
Mineral resource scarcity	kg Cu eq	7.00×10^{-3}	1.60×10^{-4}	3.05×10^{-5}	$1.75 \times 10^{+0}$	3.01×10^{-3}	4.17×10^{-1}	$\mathbf{2.18 \times 10^{+0}}$
Ozone formation, human health	kg NO_x eq	1.69×10^{-2}	1.40×10^{-4}	2.60×10^{-5}	1.62×10^{-2}	3.62×10^{-3}	6.51×10^{-3}	$\mathbf{4.34 \times 10^{-2}}$
Ozone formation, terrestrial ecosystems	kg NO_x eq	1.73×10^{-2}	1.40×10^{-4}	2.67×10^{-5}	1.68×10^{-2}	3.69×10^{-3}	6.89×10^{-3}	$\mathbf{4.48 \times 10^{-2}}$
Stratospheric ozone depletion	kg CFC11 eq	1.95×10^{-6}	3.14×10^{-8}	6.03×10^{-9}	3.13×10^{-6}	4.88×10^{-7}	1.27×10^{-6}	$\mathbf{6.88 \times 10^{-6}}$
Terrestrial acidification	kg SO_2 eq	9.82×10^{-3}	1.00×10^{-4}	1.99×10^{-5}	2.15×10^{-2}	3.34×10^{-3}	8.06×10^{-3}	$\mathbf{4.28 \times 10^{-2}}$
Terrestrial ecotoxicity	kg 1,4-DCB	$5.26 \times 10^{+0}$	5.64×10^{-1}	1.09×10^{-1}	$6.67 \times 10^{+1}$	$1.54 \times 10^{+1}$	$2.17 \times 10^{+1}$	$\mathbf{1.10 \times 10^{+2}}$
Water consumption	m^3	5.97×10^{-3}	6.62×10^{-5}	1.27×10^{-5}	7.88×10^{-2}	1.26×10^{-2}	4.36×10^{-2}	$\mathbf{1.41 \times 10^{-1}}$

resource scarcity', 'global warming' and the ozone categories, especially from the operation of the telescopic handler, which was used during the dismantling of the façade cladding.

Most processes in the selective scenario are handled locally, within 30 km of the demolition site, which is close to the same transport distance as previous studies have identified as the limit for ensuring net environmental and energetic benefits in relation to the selective demolition process (Pantini and Rigamonti, 2020). Because Denmark is only a small producer of steel, it was necessary to transport waste steel to either Sweden or Germany for recycling, and newly produced cladding must be transported to Denmark as well. This meant that 15% of CO_2 emissions in the conventional scenario came from transport. However, there may be variations in these results for different locations depending on whether the waste or the new cladding can also be transported by train or ship. Nevertheless, it shows that the benefit of local reuse is greater if there are no local alternatives for recycling or producing new façade cladding.

3.4. Assumptions and limitations

The selective demolition and conventional demolition scenarios used are based on data from an actual demolition case. On the other hand, data on transport and preparation are based on assumptions. In the actual demolition case, it was decided that the façade cladding should be reused directly, since there was a desire on the part of the purchaser that the cladding could be visible as product of reuse. This places some limitations in terms of lifespan as well as the application, since the cladding had already had a long lifespan and was generally affected by the weather. We discovered that direct reuse is often perceived as the most environmentally friendly alternative by companies because it requires less handling and preparation. However, this can also lead to a form of down-cycling because the façade cladding may have a shorter service life than new cladding, which may require panels to be replaced earlier than with new cladding. Shortening the service life will thus also lead to higher environmental impacts (Mequignon et al., 2013). This can also have an impact on whether the façade cladding can be reused again because the panels may be in such a poor condition after the original product's lifetime that they are not suitable for reuse. This issue will be relevant to investigate further in future LCAs of reuse and recycling and will relate greatly to how the environmental impacts should be distributed over the entire life-cycle of the product. This is described in more detail by Malabi Eberhardt et al. (2020) and van der Harst et al. (2016), coupled with studies of the durability of facade cladding in the second and third lifetimes of reuse.

Although this study contributes with new data on selective demolition processes, it is important to note that the results are not representative of the selective demolition of an entire building, since only the façade cladding is treated in this study. A very large proportion of the building in the case study was still demolished conventionally, as there are currently no established methods or markets for reusing concrete parts.

3.5. Implications for current demolition practice

This study has shown that selective demolition with the subsequent reuse of steel façade cladding is proven more environmentally beneficial than conventional demolition with steel recycling in at least one case, however this can vary for other types of steel cladding on other types of buildings in other geographic locations.. This knowledge may be relevant concerning the choice of materials in the design of new buildings, where there will be an environmental benefit and thus a reduction in the environmental impact of a new building if façade cladding from selective demolition is used instead of buying newly produced facade cladding. This may also be relevant for demolition companies, which, by choosing selective demolition, will be able to resell building components for reuse as sustainable materials, rather than delivering materials to waste-handling sites with subsequent recycling. However, there is still a lack of studies on the economic implications for demolition companies that choose selective demolition over conventional demolition and if the reused building parts can be an economically viable alternative to new products. We have not been authorized to publish financial data in this study, so we would suggest that future studies examining the economic aspects of selective demolition of façade cladding with subsequent reuse. The results show that the environmental impact of selective demolition was more significant than in the case of conventional demolition because machinery had to be operated for longer periods. This suggests that the machinery used in selective demolition be replaced with electric-driven machinery to help reduce e.g. CO_2 and particle emissions and reduce machinery noise at the demolition site. In addition, alternatives to protective layers of façade cladding should be explored since zinc protection had a large contribution to environmental impact.

This study only examined steel façade cladding. Since the sensitivity analysis showed that results were sensitive to changes in the weight of façade cladding, it is also relevant to investigate the selective demolition of several different types of façade cladding, which can vary in both layout weight and materials. This can affect how long the selective demolition takes, as well as which machines and tools are needed. Selective demolition with the subsequent reuse of building components is still a niche area, as most waste is still demolished conventionally and subsequently sorted for recycling at the demolition site. At present, there is no legislation governing the selective demolition and reuse of components in Denmark. However, new CO_2 requirements for construction will make reusing materials more attractive and increase the demand for sourcing more components from selective demolition.

4. Conclusions

This study has investigated the environmental benefits of using selective demolition on façade cladding rather than conventional demolition using LCA. We found that the environmental impacts of the demolition process itself were greater in selective demolition due to the longer machinery operating times. However, when looking across the full cladding life-cycle, the average environmental impact scores across all impact categories were 40% lower for the selective scenario compared to the conventional baseline scenario. Here it was the zinc protection that was added to façade cladding that had the greatest impact on the environment. In addition, the study also showed the environmental benefits of treating reuse locally so as to reduce the transportation distances of materials. Future work should explore the impact on product lifetimes for different degrees of zinc protection, as well as the merits of other possible alternative forms of protection, to reduce the environmental impact of both preparations for cladding reuse and the production of new façade cladding. In addition, it will also be relevant to study further the entire life-cycle of reused façade cladding, as well as its contribution to environmental impacts over the total evaluated life-cycle. In addition, future LCA studies of selective demolition and reuse could also be extended to other façade types and materials.

Credit author statement

Rune Andersen: Conceptualization, Methodology, LCA Software modeling, Writing. Anders Stokbro Ravn: Conceptualization, Data collection, Methodology. Morten Walbech Ryberg: Conceptualization, Methodology, Uncertainty analysis, Reviewing and Editing.

Supplementary material

Table S1-S5

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106430.

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Conference Paper 2

CP2: Adaptation of circular design strategies based on historical trends and demolition patterns.

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Adaptation of circular design strategies based on historical trends and demolition patterns

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Abstract. With new knowledge on current trends in construction and demolition, circular design strategies can be adapted to recent developments in construction, thereby providing knowledge about the potential for reducing global warming, resource consumption, and the amount of construction waste. By examining data from public registers on historical demolitions and building statistics, it is possible to examine the patterns in demolished buildings to uncover which building factors may influence whether buildings are demolished or renovated. In the following, data from demolitions in Denmark will be linked to data for newly built and existing buildings. The results show that factors initiating demolition are distributed differently between high- and low-population areas. Furthermore, the increase in new forms of construction means that circular design strategies such as reuse, recycling, and adaptive reuse can only cover a small proportion of the need for new construction.

1. Introduction

The construction industry is responsible for about 40% of all anthropogenic CO_2 emissions [1] and produces 34% of the all waste in OECD countries [2]. Construction is therefore an important focus area in reducing global warming, resource consumption, and the amount of waste. By maintaining and renovating buildings, it is possible to extend their lives, thereby avoiding demolition and reducing the need for the construction of new buildings. However, due to the scientific focus on new construction, there is a lack of knowledge concerning why some buildings are being demolished [3] instead of renovated or transformed, and to what extent these demolitions can provide circular construction materials and elements to cover the need for materials to carry out new construction. In several contexts such as LCA (life cycle assessment), it is assumed that buildings will be demolished when they reach a certain age. In relation to the environmental impact, therefore, a building's year of construction is decisive in deciding when it should be demolished. Studies show that other building-specific factors than age may be more significant concerning whether buildings will be demolished: for example, the number of floors or type of materials may be more determining factors [4]. Other relevant factors may be economic, such as the cost of housing and the potential net salvage value of the building [5]. A reduction in the local population may also lead to a declining need for housing, resulting in a larger number of vacant buildings needing to be demolished [6]. At the same time, the existence of vacant buildings in an area often has a significant impact on local sales prices for housing, leading to a greater risk of more vacant buildings and final demolition [7]. By applying circular design strategies when renovating or transforming buildings at risk of demolition, it is possible to contribute local social, economic, and global environmental benefits [8]. Alternatively, former industrial buildings can also be repurposed through adaptive reuse, thereby reducing the need for new materials. However, if a building cannot be beneficially preserved from an economic, social, or environmental point of view, it is still essential to consider circular strategies such as urban mining and still attempt to achieve environmental or economic benefits from demolishing the building by recycling or reusing the materials. By examining data from public registers on historic demolitions and building statistics, it is possible to examine patterns in the demolished buildings to uncover which factors may influence whether buildings are demolished and how we can adapt circular design strategies. This is possible by gaining access to high-quality data from Danish municipalities regarding annual rates of demolition, which can then be linked to public data on building registrations. The data can then be used to answer the following questions: i) Are trends in new construction and demolition evenly distributed between cities and sparsely populated areas? ii) Does the demand for housing mean that other building types will be demolished? And ii) Can materials from demolition realistically meet our need for new construction materials?

2. Methods

2.1. Data collection

Data on new construction, extensions, and existing buildings are extracted from the data portal by Statistics Denmark. The following databases have been used: i) BYGB34 [9], ii) BYGV22 [10], and iii) BYGB12 [11]. The BYGB12 database is an annual inventory of the number of buildings in Denmark from 2010 to 2021 divided by area, building use, area interval, and ownership. BYGV22 is a statement of construction activity per quarter from 2006 to 2021, separated by the number of buildings, and new construction areas and extensions divided by area, building use, and construction time. To calculate the size of the existing building stock, BYGB12 data from 2011 to 2021 for the total existing building area were used, divided by area, year of construction, and building use. This study only includes the above-basement floor area from BYGB12. Data for calculating demolition rates have been extracted from the Danish Building and Dwelling Register (BBR). BBR was established in 1976 and is the Danish national register that contains information about all Danish buildings and their technical facilities. BBR is publicly available and can be accessed through various online portals for single properties, regions, and nationally. As there is no portal for accessing data on demolition in BBR over a longer period, for this particular research the BBR administrator made an extract of all demolition cases reported by municipalities with associated historical BBR information on the demolition cases. The dataset contains 152,300 cases of demolition completed in the period from February 2000 to June 2020.

2.2. Data-handling

To investigate demolition trends, the annual demolition rate (see equation (1)) for different construction periods and different building uses is calculated.

$$\mathrm{DR}_{x,y}=\frac{\mathrm{D}_{x,y}}{\mathrm{E}_{x,y}} \tag{1}$$

Where DR is the demolition rate in year x for construction period y. $D_{x,y}$ is the total floor area demolished in year x for construction period y. $E_{x,y}$ is the total floor area of the existing building stock on the first day of year x for construction period y. To calculate the demolition rate for building use, y represents the specific building use instead of the construction period.

In the analysis, the national data represent a sparsely populated area, although the national dataset also contains data for densely populated areas. To represent a densely populated urban area, an area called the Copenhagen region has been defined from the database. This area is defined by combining data for Copenhagen municipality with data for sixteen densely populated surrounding municipalities: Frederiksberg, Dragør, Tårnby, Albertslund, Ballerup, Brøndby, Gentofte, Gladsaxe, Glostrup, Herlev, Hvidovre, Høje-Taastrup, Ishøj, Lyngby-Taarbæk, Rødovre, and Vallensbæk. There have been ongoing restructurings in BBR and to the requirements for registration. We therefore assessed that before 2011 there were too many errors and deviations to make an accurate overall dataset for demolition. In addition, datasets from Statistics Denmark on existing buildings have only been compiled since 2011. As a result, 2011 was chosen as the start year for the study.

3. The existing building stock

In 2019, Danish building stock had a total area of 749,496,000 m^2 [9] divided into 4,474,174 buildings [11]. The building stock in the Copenhagen region accounted for 13.5% of the total building stock in Denmark in 2019. Of that total, housing accounts for the vast majority in square meters, with a total share of 45% nationwide. In the Copenhagen region, the share of housing is much larger, at 61% of the total building stock in the region. Multi-family houses account for a large part of the housing, whereas single-family houses make up the largest housing share (see Figure 1) nationwide.

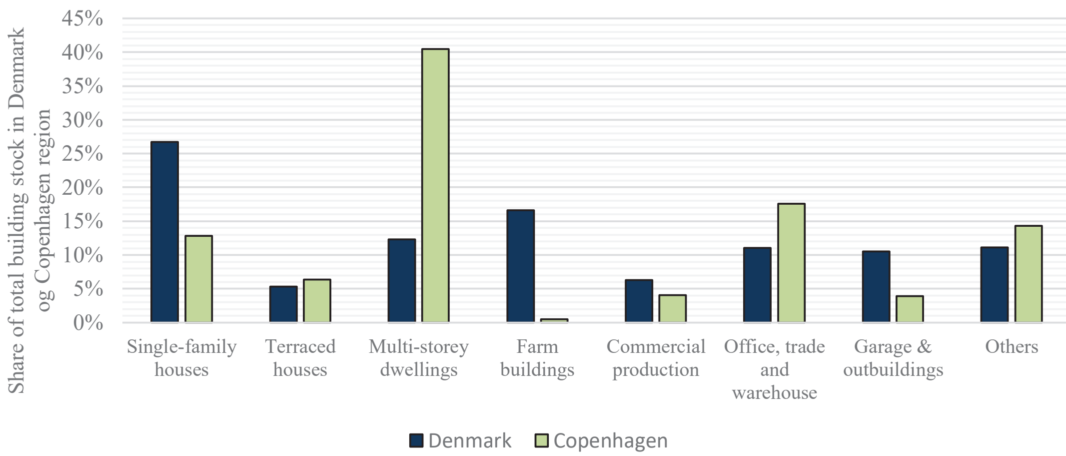

Figure 1. Distribution of building area in relation to different building uses in Denmark and the Copenhagen region in 2019.

4. New construction

The amount of new construction in Denmark peaked in 2008 at 9,428,614 square meters. From 2008 to 2011 there was a 48% annual decrease in new builds (see Figure 2). After 2011, new construction in Denmark began to increase, but in 2019 was still 22% below the peak level of 2008. In the Copenhagen region, the trend is different than in the rest of Denmark. In the Copenhagen area there has been much more growth in new construction since 2011, which means that in 2019 74% more new construction in square meters was built compared to before the financial crisis of 2008. In 2019, new construction in Copenhagen accounted for 17.5% of total new construction in Denmark, even though the existing building stock in Copenhagen only accounts for 13.6% of the country's entire building stock. This means that new construction in Copenhagen is higher than in the rest of the country. Concerning the expansion of existing buildings, overall there has been a decrease in the total area of extensions in Denmark generally and in Copenhagen specifically. Nationally, the annual floor area of extensions has decreased by 58% from 2006 to 2020, and in Copenhagen by 48%. While the expansion of existing buildings fell over the period, the area of new buildings increased, which could indicate that new construction is being preferred over extensions of existing buildings. Therefore, we should ask whether this also means that demolition subsequently replaced by new construction is preferred over extensions of existing buildings.

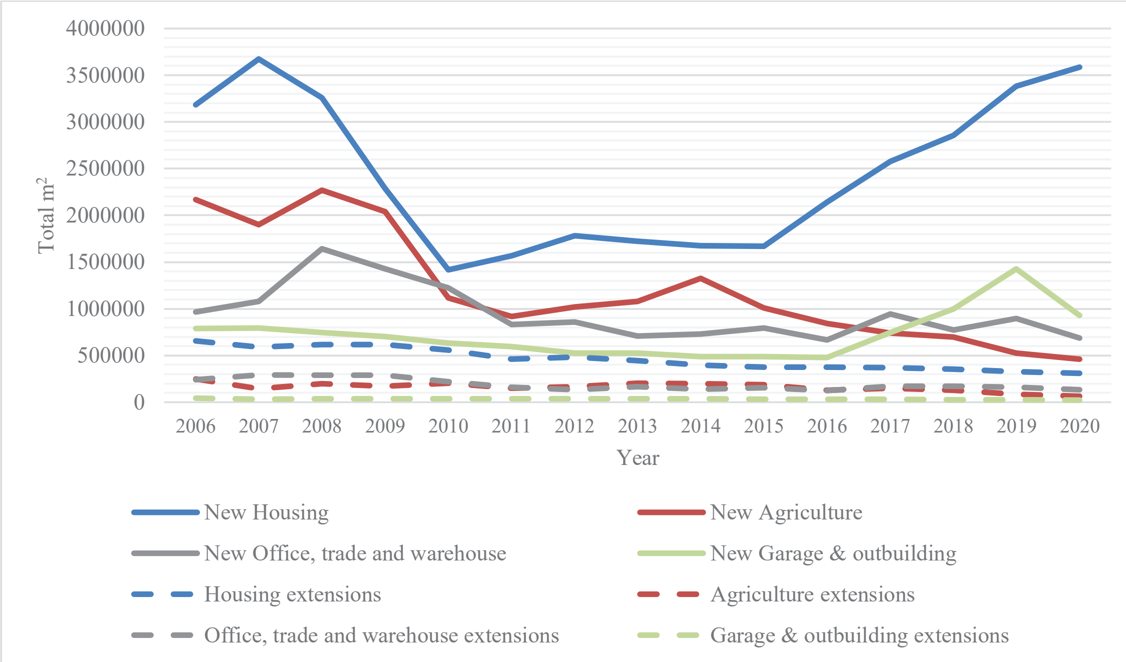

Figure 2. Overview of the annual square meters of new construction and extensions in Denmark from 2006 to 2020.

When the total area of new builds is split into different building uses (see Figure 2), a different pattern emerges regarding the various building uses, one that deviates from the general trend. The increase in new builds is mainly driven by constructions of new dwellings, which accounts for 46% of all new construction in Denmark in 2019 and has been increasing since 2010. On the other hand, new construction of farm buildings and offices, shops and warehouses has declined since the financial crisis of 2008, indicating a declining demand for these building types. The new construction of garages and small buildings also declined in the past, but it experienced a significant increase since 2016. New constructions of garages and small buildings accounted for 19.5% of all new construction in 2019, even though this building use only accounts for 10% of the total existing building stock. In Copenhagen the same trend is seen, but here garages and small buildings make up only 4% of the entire building stock.

5. Demolition

5.1. Demolition rates for different building uses

Nationally, the average demolition rate (i.e. $DR_{x,y}$ as estimated using equation (1)) was 0.24% from 2011 to 2019, and 0.19 % for the Copenhagen region. Concerning the factors that can lead to decisions to demolish, Figure 3 show some general tendencies whereby the demolition rates for housing are substantially lower than for buildings with industrial applications. Moreover, the demolition rate for industrial construction in densely populated areas tends to be substantially higher than the average demolition rate for industrial buildings in Denmark. Here, it is especially production buildings that are at greater risk of being demolished if they are located in urban areas.

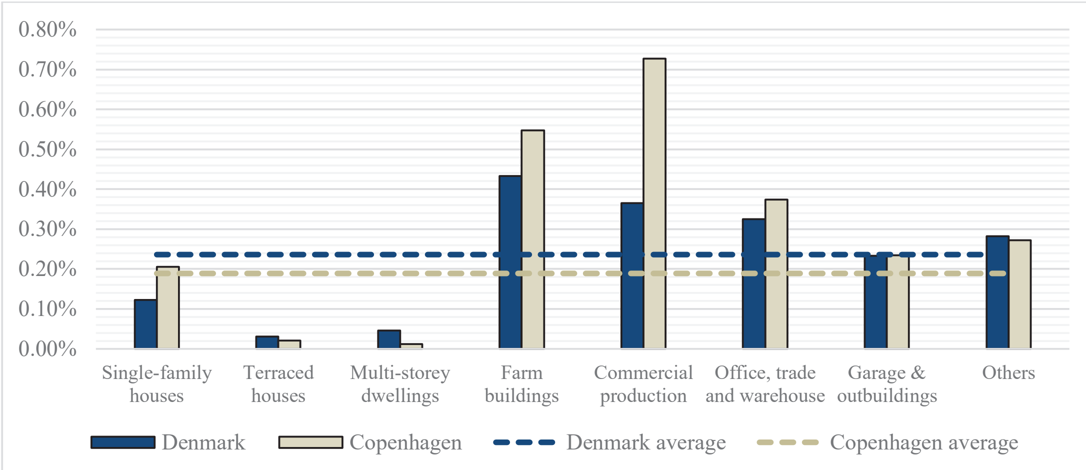

Figure 3. Average demolition rates for different building uses in Denmark and the Copenhagen region from 2011 to 2019.

In addition, the results show that for housing there is also a difference between Denmark and Copenhagen, the demolition rate for single-family homes being greater in Copenhagen than the national demolition rate for single-family homes. In contrast, the demolition rate for multi-family dwellings is as low as 0.01% in Copenhagen, or five times lower than the national demolition rate for multi-family homes.

5.2. Demolition rates for different construction periods

When the demolition rate is calculated over different construction periods (see Figure 4), two different and opposite trends emerge between Copenhagen and Denmark, where old buildings in Copenhagen are at much less risk of demolition than old buildings in the rest of Denmark. For buildings in Copenhagen built before 1909, the demolition rate is around 0.05%. After that, the demolition rate increases the younger the buildings are, reaching its maximum of 0.39% of the existing building stock for buildings built from 1950 to 1959, both for buildings demolished in the Copenhagen region and nationally. After that, the rate of demolition begins to decrease again.

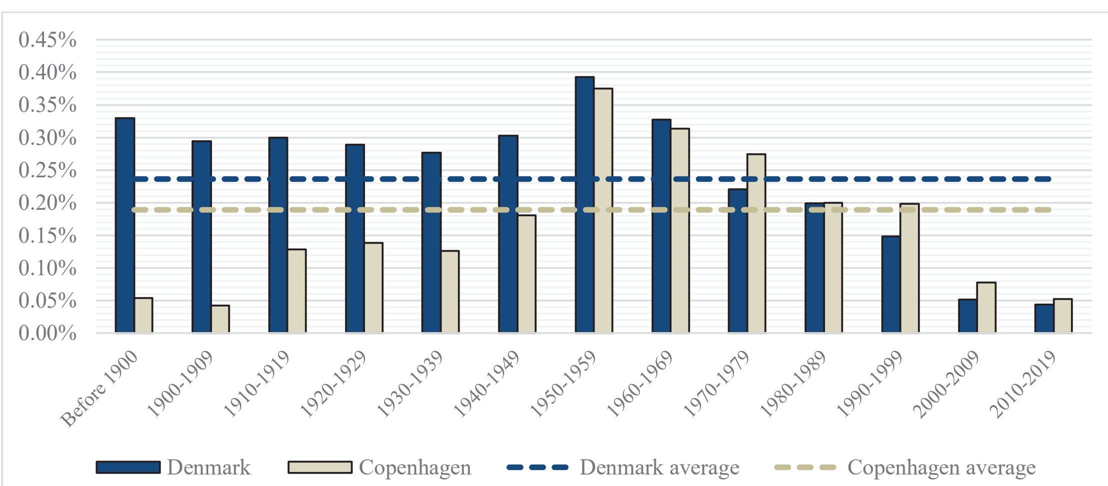

Figure 4. Average demolition rates for different construction periods in Denmark and the Copenhagen region from 2011 to 2019.

The demolition rate for old buildings in Denmark generally is substantially higher than in Copenhagen and is more evenly distributed over construction periods before 1950. After that, the demolition rate for new buildings falls more markedly at the national level than it does in the Copenhagen area. The results show that a building located in densely populated areas or rural zones is at equal risk of being demolished for buildings built between 1950 and 1969. In addition, the results of buildings before 1950 are at much less chance of demolition in the Copenhagen area than they are in the rest of the country. In contrast, the opposite is true for buildings built after 1970, which are at the most significant risk of demolition if they are located in the Copenhagen region.

5.3. Demolition in relation to new construction and extensions

From 2011 to 2019, the proportion of demolitions in Denmark remained very constant, with 0.20-0.28% (see Figure 5) of the existing building stock being demolished annually. The year with the most demolitions was 2015, when 2,017,166 m^2 were demolished in Denmark, whereas 2013 was the year with the fewest demolitions, when a total of 1,444,495 m^2 were demolished.

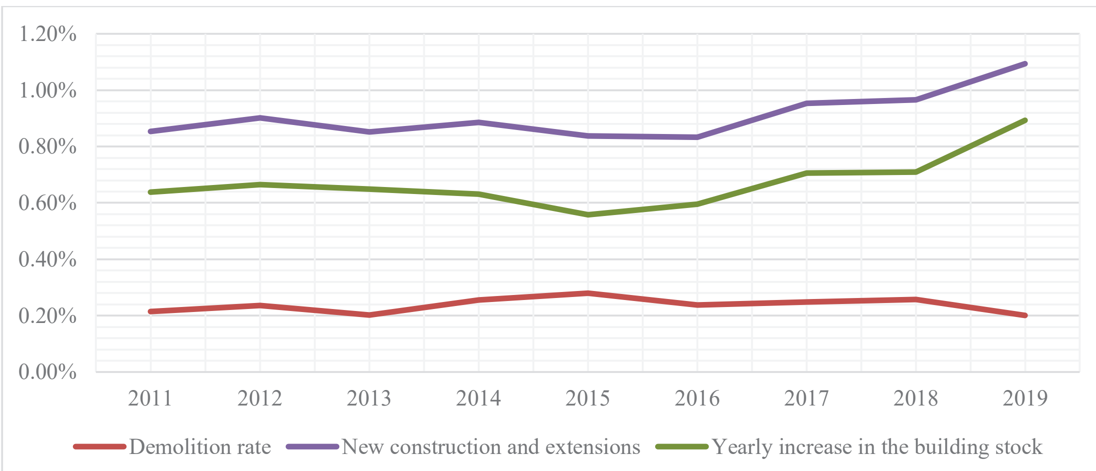

Figure 5. Development in the share of new construction, extensions and demolitions in Denmark in relation to the existing building stock from 2011 to 2019.

Over the entire period, the average demolition rate was around 0.24% of the existing building stock. On the other hand, an average of 0.75% new construction and 0.15% extensions was added to the existing building stock from 2011 to 2019. Thus, there is a growth in the existing building stock of 0.67% over the period when demolition is deducted. At the same time, the share of new construction is increasing, while the share of demolition is static. This can therefore be a problem concerning the recycling of building materials since the proportion of available materials from demolition is not increasing at the same rate as the need for reused or recycled materials for new buildings. Over the period 2011 to 2019, square meters demolished corresponded to 25% in relation to how many square meters were being built. In 2019 square meters demolished only corresponded to 18% of the total of new construction in square meters. In addition, there are a lot of materials from demolitions that are not suitable for either reuse or recycling because they contain harmful substances or provide limited opportunities for recycling. This means that demolition can only cover a small proportion of the materials needed for new construction. According to the Danish national inventory for construction waste in 2019, the recycling rate for construction waste was 36% [12] in 2019. This means that only 6.5% of the material requirements of new construction in 2019 could be covered from demolitions in the same year when recycling rates are added to the share of demolition if it is assumed that there is an equal relationship between material in a demolished square meter building and a square meter newly constructed building. Of course, this will not be correct in most cases and is therefore used only as a theoretical assessment of the magnitude of the potential for circular materials.

6. Adaptation of circular design strategies

These results show a difference in demolition trends between densely and sparsely populated areas. In densely populated areas, newer buildings were at greater risk of demolition than older ones. This could be important knowledge concerning the environmental impact of circular design strategies for existing buildings. In life-cycle assessments, generic life-times for buildings are usually used in calculating the remaining lifetime of the building. However, the results in this paper suggest the relevance of considering remaining life-times differently, depending on whether the building is located in sparsely or densely populated areas. Concerning circular design strategies, the results demonstrate the potential for adaptive reuse, since there is a decreasing demand for industrial buildings, which also accounted for a large share of the demolitions. With circular design strategies, such as adaptive reuse, these industrial buildings can be transformed into dwellings, avoiding demolitions while reducing the demand for the construction of new housing. In the case of adaptive reuse, it will primarily be the load-bearing construction elements that are preserved, which are also the building parts that are often most difficult to recycle and reuse offsite. This is in contrast to conventional demolition, where, for example, concrete from the demolition of industrial buildings is down cycled to replace gravel. However, adaptive reuse requires industrial buildings located in areas where there is a demand for housing, as in densely populated areas. Unfortunately, our results showed that farm buildings located in sparsely populated areas accounted for a large part of the demolition. In cases where adaptive reuse is not advantageous due to a falling demand for buildings, circular strategies such as urban mining offsite reuse and recycling of material from demolition may be necessary in order to avoid having a lot of vacant buildings. If a more substantial proportion of buildings are renovated or transformed with adaptive reuse, it will also mean that the proportion of available materials from demolitions will decrease. In order to meet the very large need for materials for new construction, circular design strategies are needed that reduce the need for new construction. For instance, building smaller units or using environmentally friendly low-carbon materials will not reduce the amount of materials significantly, but will lower the environmental impact.

7. Limitations and assumptions

This study only includes new construction and extensions since it was not possible to obtain data on renovations. Nonetheless, renovations are a circular method of avoiding demolition. Renovations both generate construction waste and require new materials. Because only 36% of materials are recycled, renovations will mean a much greater need for new materials. Demolition can cover about 6.5% of the need for new materials in new constructions, a value that would probably be lower if the material needs for renovations were included. However, this will require a greater degree of registration of how many square meters are being renovated per year and the type of renovation. Also, it must be taken into account that the material intensity can vary between demolished buildings and newly built buildings and therefore the 6.5% can vary based on which types are demolished and which types of buildings are built so the 6.5% should be seen as a general average consideration of the entire building stock, This study does not cover materials intensities for buildings, so the actual material quantities may differ because the material intensity will vary for different buildings per m^2. A thorough study of the material intensities of Danish buildings is needed before it will be possible to calculate material flows. However, by stating the inventory as 'per square meter', it will be possible later to include material intensities. The results give an impression of the trend in and size of supply and demand.

8. Conclusion

By combining high-quality building data from Danish building registers, this project has defined and tested trends in new construction, existing buildings, and demolition that can affect circular design strategies. This showed that factors influencing demolition decisions are distributed differently between densely and sparsely populated areas. The age of a building is often described as an essential indicator of when it will be demolished, but our analysis of demolition data showed that newer buildings were at greater risk of demolition in densely populated areas. In contrast, the opposite trend occurs nationally, where it was older buildings that were at the greater risk of demolition. In addition, the results also showed a large proportion of industrial buildings being demolished but a decrease in new constructions of industrial buildings. In contrast, there was a significant increase in new housing construction, but a very low demolition rate of housing so there is a basis for transforming more industrial buildings into housing through circular design strategies such as adaptive reuse. At the same time, significant increases in new construction mean that circular design strategies such as reuse, recycling, and adaptive reuse can only cover a tiny part of the need for new housing. This means that there is a great need for other sustainable strategies, such as reducing the need for new construction or using low-carbon materials, in order to reduce global warming, resource consumption, and the amount of generated construction waste.

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Journal Paper 4

JP4: Lifespan prediction of existing building typologies.

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Lifespan prediction of existing building typologies

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ABSTRACT

Life-cycle assessment (LCA) is currently one of the construction industry's most widely used methods of environmental assessment. Because LCA calculations is based on life-cycle thinking are the lifespan of the building a sensitive parameter in relation to the calculated overall environmental impact of the building. More accurate assessments of the lifespans of buildings are therefore a prerequisite for reducing errors and uncertainties in LCA and Life Cycle Costing (LCC) calculations. This study evaluates a generalized logistic lifespan prediction model for existing building typologies. The model is tested as part of a Danish case study based on building data collected from 124,096 cases of demolition. The objective is to investigate whether the typical lifespan used in LCA or LCC calculations accurately describes the remaining service life of existing buildings based on different building typologies and construction periods. The study show that office buildings generally have much shorter expected lifespans than previously assumed and that multi-family housing has nearly twice the lifespan of single-family housing. The results show a tendency for a declining lifespan based on the construction period, in which newer buildings, i.e. those that are no more than thirty years old, have a lifespan that is much shorter than the average lifespan for all construction periods. These results are highly relevant for both LCA and LCC calculations of buildings since they indicate that newer buildings in northern Europe have a lower lifespan than previous studies have shown.

1. Introduction

The construction industry is responsible for 40% [1] of all anthropogenic CO_2-related emissions and is one of the industries that contributes the most to global warming. As an attempt to measure the environmental impacts of individual buildings, different standards have established principles of calculation by issuing general guidelines for LCA (Life Cycle Assessment) [2] and building-specific standards [3–5]. LCA is the construction industry's most widely used method of environmental assessment [6], and its application is still increasing, as it is also used as a regulatory tool in European policies [7]. For instance, Denmark [8] and the UK [9] are enforcing mandatory LCA calculations for new buildings. Despite standardization and direct implementation in policies, studies show inconsistency related to known and expected service life or lifespans in End-of-Life (EoL) modelling [10–12]. Choosing an arbitrary lifespan for a building introduces a substantial amount of error into the LCA, as there is a significant correlation between the environmental impact in respect of used energy and the building's service life [13]. As a result, increasing a building's lifespan substantially reduces its environmental impact [14,15]. The most commonly used building lifespan in LCA and Life Cycle Costing

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(LCC) studies is either fifty or a hundred years, depending on the building structure [16]. Lifespans of buildings (calculated from the proportion of building stock registered as demolished) have been found to range from ten to eighty years in other studies, as summarized in Table 1.

Increasing the lifespan of a building from 50 to 100 or 150 years can result in theoretical reductions in the whole life-cycle, with embodied energy being calculated of 16% (100 years) and 29% (150 years) respectively [22]. Building components have different lifespans, so any change in a building's lifespan may mean that some building components have to be replaced more often over time [23]. Replaced parts such as insulation and windows contribute more to the overall impact in buildings with long lifespans, whereas a material such as concrete accounts for a larger share of the total emissions in short-lived buildings [10]. In addition, an extension of the lifespan of the building in LCC calculations may mean that operating energy accounts for the majority of the building's life-cycle costs when it has a lifespan of more than thirty years [24]. The lifespan of buildings is one of the parameters with the greatest level of uncertainty in LCA and LCC calculations, since it is difficult to know how long future buildings will stand before they are demolished [25]. One way of obtaining more valid LCA and LCC calculations and reducing the uncertainty [26] may be to create a better basis for a more accurate prediction of the remaining lifespan of existing and new buildings. Suppose data is available on the construction year and demolition year of buildings. In that case, it is reasonably straightforward to calculate the average building lifespan of demolished buildings within a specific building typology, as demonstrated by several research projects [12,17–19]. It is less simple to predict the future lifespan of buildings, so research should be encouraged to develop better prediction models that can be further applied to

Table 1
Studies including lifespan predictions of buildings.

Title	Building lifespan	Data	Model	Country
Building lifespan prediction for life-cycle assessment and life-cycle cost using machine learning: a big data approach [16]	Average = 22.8 years Wood = 52.6 years Block = 31.3 years Brick = 29.3 years Concrete = 22.8 years Masonry = 19.9 years Steel = 10.7 years	971,514 cases of demolition	Linear regression, XGBoost, LightGBM, Deep Neural Network (DNN)	South Korea
Factors influencing the service lifespan of buildings: an improved hedonic model [17]	Average = 34 years Residential = 35 years Commercial = 32 years Office = 29 years Industrial = 30 years Other = 42 years Average = 34 years	1732 demolished buildings	Hedonic regression	China
Impact of lifetime on US residential building LCA results [12]	Residential = 61 years	3700 buildings	Mean age of demolished buildings	USA
Lifetime distribution of buildings decided by economic situation at demolition: D-based lifetime distribution [18]	Thirty years over all construction periods	Yearly existing and constructed floor area from 1983 to 2010	Time-series analysis Mean age of demolished buildings	Japan
Low-carbon scenarios for higher thermal comfort in the residential building sector of Southeast Europe [19]	before 1945 = 75 years 1946–1980 = 80 years 1961–1970 = 65 years 1971–1980 = 75 years 1981–1990 = 65 years	Not clear	Weibull distribution	Serbia, Montenegro and Albania
Lifespan of building components when assessing sustainability and total economy [translated from Danish] [20]	Buildings overall = 100 years Housing = 120 years Agriculture = 40 years Production = 80 years Transport = 60 years Office & shops = 80 years Leisure and sport = 60 years Outbuildings = 40 years	Existing building-stock area in 2012	Mean time to failure (MTTF) calculation based on 1% yearly demolition rate	Denmark
Modelling global material stocks and flows for residential and service-sector buildings towards 2050 [21]	Residential = 60 years	Japan, China, US & Europe	Weibull distribution	Global

existing building standards [27]. In Denmark, the standardized lifespan for buildings based on a mean time to failure calculation is based on a linear annual reduction of the existing building stock [20]. Recently the lifespan calculation has been revised [28] in which the standard lifespan of buildings are based instead on a combination of deterministic and heuristic analysis. However, the calculation still depends on the known service life and roughly prescribes the future lifespan remaining to buildings based on a presumed correlation between a demolition rate based on the period 1994–2012 and future construction activity. The authors warn that estimates are inherently subject to great uncertainty, and will certainly vary considerably over the years. Supporting this concern [29], showed the weakness of relying on old demolition rates and that updated lifespans diverge greatly from service life. Even though the study was based on limited data (20,000 demolition cases) between 2009 and 2015, the authors noted that the average lifespan of buildings summarized in overall application categories for all building types is ill suited to LCA. Here we will expand the data foundation for the demolition and lifespans of existing buildings and use Denmark as a case study, since it is one of the European countries with the largest amounts of publicly available registered data on buildings [30,31].

This study therefore aims to evaluate how we assess and calculate lifespans for different existing building typologies using a generalized logistic model. The model is tested in a Danish case study based on data collected on 124,096 cases of demolition. The objective is to investigate whether the lifespan typically used in LCA or LCC calculations accurately describes the lifespan of existing buildings based on different building typologies and building periods.

2. Methods

2.1. Demolition data

The lifespans calculated in this study are based on data extracted from the Danish Building Register (BBR) on 124,096 buildings demolished between 2007 and 2020 [32]. Data for each case of demolition includes the date of the demolition, the building's year of construction, its floor area and its use. The BBR is the national centralized Danish register of existing buildings. The data are created based on the notification of demolished buildings reported to municipalities by building owners. When a building is reported as having been demolished to the municipality, the building is subsequently deleted from the BBR register and is therefore no longer visible in the publicly available registers. A complete dataset of reported demolitions in the associated information in the BBR is created by merging a list of the annually reported cases of demolition in the BBR with the annually stored historical registered BBR data for the demolished buildings in question. Subsequently, the data has been sorted to improve its quality by removing buildings with missing registrations of demolition date, floor area or use. The registrations before 2010 were found to deviate due to restructurings in the BBR framework, so demolition cases from before 2010 were removed to create a uniform dataset. The cleaning of the data resulted in a final dataset of 104, 927 cases of demolition carried out in all Danish municipalities from 2010 until the end of 2019.

2.2. Building stock data

Data on the floor area of existing buildings in Denmark are extracted from a Statistics Denmark database called BYGB34 [33]. The dataset includes the total building area of existing buildings as registered on the first day of the year from 2010 to 2022, divided into construction periods and building uses. Data on new construction and extensions of existing buildings are extracted from database BYGV22 [34].

2.3. Lifespan of buildings

The average lifespan of buildings demolished from 2010 to 2019 is calculated based on the data set containing the 104,927 cases of demolition. The total demolished floor area in the dataset is 17,135,730 m^2. The average lifespan of all demolished buildings is calculated based on the number of buildings $\bar{t}_{N(t)}$, where t is the individual building lifespan in the dataset (see eq. (1)). Alternatively, the average lifespan of buildings is calculated based on their floor area using a floor area-weighted score, $\bar{t}_{Y(t)}$ (see eq. (2)).

$$\bar{t}_{N(t)} = \frac{\sum_i (t_d - t_c)}{i = n} \tag{1}$$

Where t_d is the demolition year and t_c is the construction year for demolition case i.

$$\bar{t}_{Y(t)} = \frac{\sum_i (t_d - t_c)A}{\sum_i A} \tag{2}$$

Where A is the area for the demolition case I.

In any year, the number of square meters of building for any category or typology is given by (total building area) (see eq. (3)).

$$Y(t) = Y(t-1) + N(t) + E(t) - D(t) \tag{3}$$

Where $N(t)$ is the newly built square meters in year t, $E(t)$ is the extensions to the given building stock at year t, $D(t)$ is the demolished square meters at year t, that is a positive whole number between (2010 and 2019).

The change in building stock (see eq. (4)) is given as the differential of $Y(t)$.

$$Y'(t) = N'(t) + E'(t) - D'(t) \tag{4}$$

The predicted building lifespan is based on two different principles: a) buildings will be demolished at a continuous unchanging rate; and b) buildings will be demolished at a slow rate at the beginning and end of the average lifespan. In either case the demolition rate D′ is assumed to be independent of the rate of future extensions E′ and new buildings N'. The average lifespan of a building from a specific construction period and specific typology is thus equivalent to the simulated time until half of all buildings in the specific typology and period have been demolished.

The accumulated demolitions of buildings in any category or typology for a specific given period can be modelled as Y(t) (see eq. (3)) with a linear regression (LR) model (eq. (6)) and a generalized logistic growth function GLF model ([35]; see eq. (8)). The two models are depicted as principles in Fig. 1. The GLF models have uses in many other areas of research, including botanics [36], for projecting the performance of technologies, foreseeing population changes, conducting market penetration analyses and micro- and macro-economic studies, the diffusion mechanisms of technological and social inventions, ecological modelling [37] and more recently extrapolating COVID-19 growth patterns [38].

The demolished square meters, given at any time t, are represented by D(t) (see also eqs. (3) and (4)) where t is a positive integer representing a year in a fitting dataset. D(t), when assumed to be a linear function, is described as shown in eq. (5), when in GLF form is shown in eq. (7), and when generalized to a logistic growth function can also be represented as shown in eq. (7).

Specifically in the linear case, the sum of the initial amount of demolished square meters, Beta, and the demolished square meters at any given time, t, is expressed as the function (rho).

$$D(t) = \delta(t) + \beta \tag{5}$$

Where t is the construction year of the building in a given period, δ is the average demolition rate in m^2 in the given period, β is the initial number of demolished square meter buildings at $t = 0$.

We can thus derive the average building lifespan given the linear regression (see eq. (6))

$$\bar{t}_{LR} = \frac{D(0)/2 - \beta}{\delta} \tag{6}$$

The average building lifespan is solved recursively by solving t_0 in the logistic form (see eq. (7)).

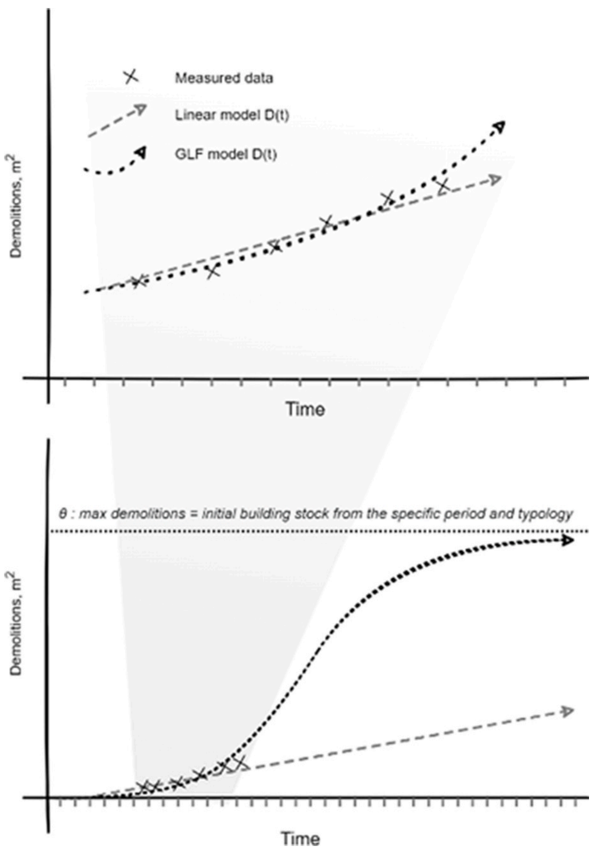

Fig. 1. Principles of modelling the lifespan of existing buildings. Top: zoomed-in high-fidelity data of the accumulated demolition of a specific building typology from one particular construction period. Below: zoomed-out data and models (linear grey, GLF black). Both models assume zero demolitions at the beginning of the period and use R2 to measure the best fit with the actual data (marked X).

$$D(t) = \frac{\theta_{max}}{(1 + \xi \exp(-\delta(t - t_0)))^{1/\xi}} \tag{7}$$

Where D(t) is the demolished square meters using a GLF model.

In the case of $\xi = 1$, the generalized logistic growth function (see eq. (8)) is written as:

$$D(t) = \frac{\theta_{max}}{1 + \exp(-\delta(t - t_0))} \tag{8}$$

Where t is the construction year of the building in given period, δ is the average demolition rate in m^2, θ_{max} is the maximum square meters of demolished buildings at time t_{max} and is equivalent to the initial number of square meters built in the period, t_0 is the average building lifespan $\cong \bar{t}$ given logistic growth.

Recursive solving of D(t) for t_0 use known θ_{max} from the dataset for each period and typology (as θ_{max} always equals the total number of square meters built in the specific period (i-j) equivalent to the new building raised, N(i-j), see also eq. (3)), R2 for fitness, while δ and t_0 are used as open parameters. Simulated anneling [39] implemented algorthimcally using Galapagos [40] are used to minimize R2.

3. Results and discussion

3.1. The lifespan of demolished buildings

The average lifespan of demolished buildings is a good indicator of the relative demolition rate of varying typologies. However, it is not a good indicator of the total building stock's average lifespan, as it only considers the proportion of buildings demolished and ignores the remaining building stock. The calculation of the average lifespan of demolished buildings in Table 2 shows considerable variation from year to year within some building typologies. The variance is most prominent in typologies containing the fewest cases of demolition each year, i.e. typologies for culture, hotels, other housing and daycare institutions individually make up less than 1% of total cases of demolition. Garages and outbuildings are responsible for 33% of the annual cases of demolition, the largest share for any building typology. The lifespan of garages and outbuildings increased from 79 years in 2016 to 318 years in 2017, a noticeable and unlikely increase in lifespan. This increase has been be introduced because of new registration methods, where satellite monitoring and GIS registration [41] is used to identify unregistered buildings that autogenerate buildings in the BBR. The dataset for demolished buildings show that these unregistered buildings are often assigned a year of construction with a value of '1000′, which explains the abnormal increase in lifespan.

The single-family typology (20% of all demolition cases) and the agriculture typology (25% of all demolition cases) have some of the most negligible variations in lifespan. The lifespan for single-family housing is the highest, with an average lifespan for the ten-year period of 99 years. Agriculture buildings have the most extended lifespan of all buildings not used for housing.

There are some noticeable changes in lifespans between Tables 2 and 3 for multi-family houses where the lifespan is reduced by 22 years when using area weighting. The results show that the lifespans of multi-family housing and agricultural buildings are the most sensitive to area weighting, which may be due to the fact that they vary more in area than e.g. single family housing.

3.2. Tendencies in changes to existing building stock

The significant change from 2017 in the total amount of registered floor area of existing buildings can also be seen in the yearly change (see Fig. 2) in floor area, which gives the false expectation of a sudden increase in the existing building stock of buildings constructed before 2010. On average, about 0.5 mil square meters of the existing building stock are demolished every year, equivalent to 0.7‰ of all existing buildings.

As expected, it is possible to model the continuing development of the total building stock with known new buildings N, known

Table 2
Average lifespan for demolished buildings in Denmark from 2010 to 2019 without weighting.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 year average
Single family	99	97	98	101	100	103	101	100	97	96	99
Terraced house	83	74	114	80	123	107	66	100	83	81	91
Multifamily residential	101	89	90	90	87	87	91	96	105	93	93
Agriculture	77	78	81	83	82	84	82	82	86	84	82
Commercial production	62	56	57	60	62	56	64	58	62	61	60
Energy	42	48	46	48	52	51	48	42	50	56	48
Transport	59	52	58	57	52	55	60	62	56	77	59
Office, trade and warehouse	58	56	58	59	63	60	66	60	64	66	61
Hotel and restaurants	58	54	56	57	71	59	59	63	81	68	63
Culture	62	62	73	115	84	69	69	71	84	72	76
Teaching and research	46	41	55	51	61	53	54	51	54	60	53
Health	66	58	54	54	58	61	63	51	58	77	60
Day-care institutions	28	36	42	39	48	47	41	42	57	55	43
Leisure and sports	52	53	55	56	54	55	57	57	57	60	56
Garages and outbuildings	53	53	61	62	61	63	79	318	368	372	62

Table 3
Area weighted average lifespan for one demolished m^2 for different building uses in Denmark from 2010 to 2019.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	10 year average
Single family	101	99	99	103	102	105	102	101	98	97	101
Terraced house	78	76	107	75	119	95	67	82	60	70	83
Multifamily residential	85	63	62	63	58	56	69	78	99	77	71
Agriculture	67	67	70	72	73	70	72	69	61	71	69
Commercial production	66	55	56	60	58	50	60	55	61	54	57
Energy	50	55	51	46	43	50	57	43	48	53	50
Transport	62	47	42	43	52	44	49	68	53	53	51
Office, trade and warehouse	46	52	53	55	58	51	58	52	59	55	54
Hotel and restaurants	65	78	65	65	88	72	64	72	99	67	73
Culture	64	51	55	109	74	66	64	71	89	60	70
Teaching and research	46	38	48	52	57	58	51	53	52	75	53
Health	59	52	41	52	55	69	67	49	53	79	58
Day-care institutions	36	39	43	47	43	53	47	48	56	54	47
Leisure and sports	53	53	58	54	56	56	57	54	56	62	56
Garages and outbuildings	65	68	75	78	75	75	84	233	276	263	74

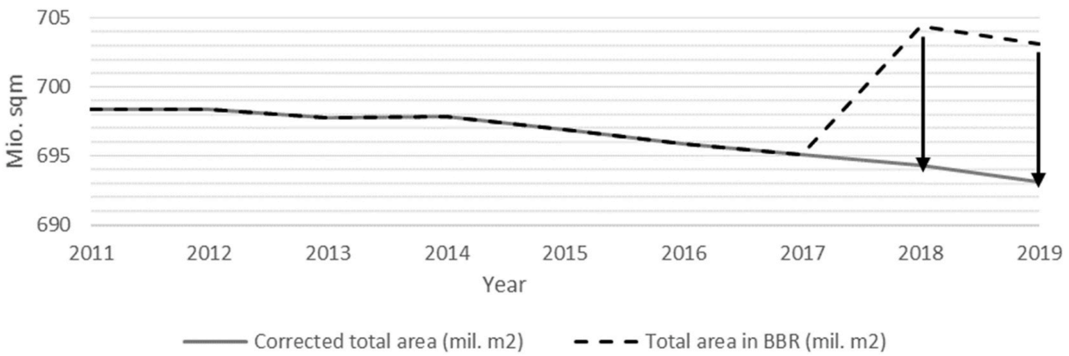

Fig. 2. Development in the total area of building stock (mil. sqm) constructed before 2010, subtracting extra added auto-generated BBR buildings (corrected area).

newly added extensions E, and known demolished buildings for the particular year D, as shown in Fig. 3 (see also eqs. (3) and (4)). Only minor variance is seen in 2017, 2018 and 2019 due to the previously mentioned need to filter out auto-registered buildings.

Considering the yearly floor area of newly constructed buildings, extensions to existing buildings and yearly demolished buildings, the building stock grew from about 700 to 750 million sqm from 2011 to 2019, equivalent to 7‰ growth in the period. This also means we see a difference of a factor of ten between the amount of demolished and newly added square meters in this period.

3.3. Fitting linear and nonlinear models to the existing building stock

When fitting linear (LR, eq. (5)) and logistic functions (GLF, eq. (8)) to the data and calculating D(t), the linear R2 is 0.94, MAE (Mean Absolute Error) 0.004, RMSE (Root Mean Square Error) 3.85, while the logistic R2 is 0.97, MAE 0.001 and RMSE 3.98. These functions estimate the yearly building stock state D′(t) pre-2011, which again is used to position (but not predict) the cumulative rate

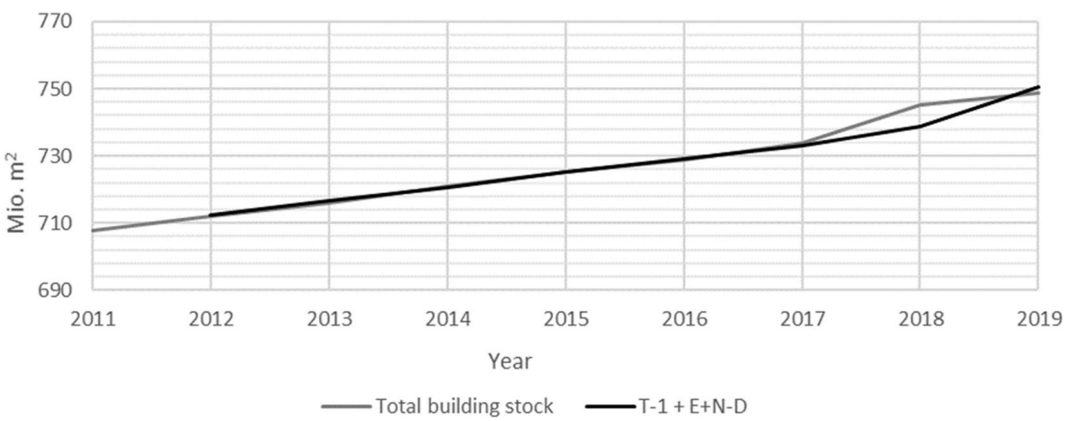

Fig. 3. Development in the total area of building stock (mil. sqm) from 2011 to 2019, subtracting extra added auto-generated BBR buildings.

of D(t) of the post-2019 predictions of lifespans. The D(t) is calculated using two different perspectives of future building demolition rates. Scenario 1 assumes the fewest possible demolitions per year based on the current linear interpretation of data, as it ignores in-period growth and assumes a flat rate of demolitions across all typologies and periods. It uses the linear pre-2011 estimate expected in period building-stock sizes to fit the LR model accordingly, as shown in eq. (5). The fit is adjusted independently of typology and periods. Scenario 2 assumes the maximum possible demolitions per year based on logistic growth seen in the data. This scenario includes in-period development, adjusted independent typology and period building stock pre-2011 on the GLF (logistic regression) model (see also eq. (8)).

Both models fit in the dataset with a high degree of confidence (see Fig. 4), the linear regression model performs better for our dataset compared to the South Korean data [16], and the logistic model is outperformed by the Deep Neural Network when measuring RMSE only. To this extent, the logistic model as a baseline best explains the demolition data on a par with deep neural network models. Nonetheless, to obtain the "actual" mean lifespans of buildings, the entire building stock needs to be taken into account, not only demolished buildings. As a result, the LR and GLF models are applied to the building stock dataset.

3.4. Expected lifespan for existing buildings

The two models predict vastly different building lifespans, both in scale and across the various periods of the construction year. When comparing the mean absolute error and coefficient of determinations, the logistic model depicts a 3.5 times higher likelihood of fit and a 60% lower mean error rate than the linear model (see Table 4). The probability of a building being demolished increases with its age as captured in the rate of change per decade comparing the linear models (e.g., comparing the 1980s with 1990s′ lifespans). However, the linear model does not capture this tendency in the function itself, in contrast to the logistic model (see Fig. 5) (see Fig. 6).

The logistic model captures the logistic growth for each period with the fundamental premise of increasing the likelihood of demolition over time until a break-even point is reached where demolitions for the particular period begin slowing down. This dynamic change differs from period to period, resulting in varying predicted lifespans. Some periods are captured with high confidence, while others are not. Consequently, the linear model predicts unrealistically long average lifespans and serves as a maximum boundary for a building's lifespan, unadjusted for any change in the rate of demolition over time. While we may see a rationale for the cultural protection of buildings, as we rarely see ancient buildings demolished, the same reasoning does not apply to residential buildings that are fifty to seventy years old. This tendency is shown in the logistic model but not in the linear model.

The results shows correlations between the different periods and the typology. Compared to the study by Ref. [16], the correlations are ten to a hundred times better than when attempting to find patterns in materials (mainframe) and regions. An interesting aspect of the results is that buildings across all typologies constructed after 1990 have the shortest expected lifespan in the logistic model and the longest expected lifespan in the linear model. The most probable prediction is the GLF model of office buildings, which is significantly more likely than the LR model. Assuming that any of the two models can describe future demolition rates, it is possible to deduce further the composition of Denmark's buildings constructed before 2019, this is shown in Fig. 7 for residential buildings and Fig. 8 for office buildings. The two figures show that, with GLF modelling, the oldest constructed buildings will in the future make up a much larger proportion of the existing building area of all buildings built before 2019.

The two models create very different expectations for the composition of buildings (see Figs. 7 and 8). Most prominent is the expectation that office buildings that are considered old today (built before 1900) will outnumber any other office buildings constructed between 1900 and 2010 when using the model with the highest confidence (GLF). Both models agree that office buildings built between 1940 and 1969 will be almost non-existent in 2210.

Treating the linear regression model as the lower boundary and the logistic model as the upper boundary of the demolition probability rate results in convergence in Fig. 9 before year 2200 for office buildings and after year 2200 for agricultural and residential buildings. The average building lifespan aligns with the 50% mark, which again explains the much higher variance of an average lifespan expected for residential buildings than offices and agricultural buildings. As mentioned previously, the LR model is not well suited to explaining building lifespans compared to the GLF model, though in seeking to model future expectations of building lifespans, political and commercial changes may affect the lifespans of some or all types of building. In this sense, the lower boundary (LR) should be interpreted as the political/commercial landscape seeking to preserve as much as possible. The upper boundary (GLF) is when no change in policies or commercial interests will occur. Any political or market-driven actions to increase demolition rates will

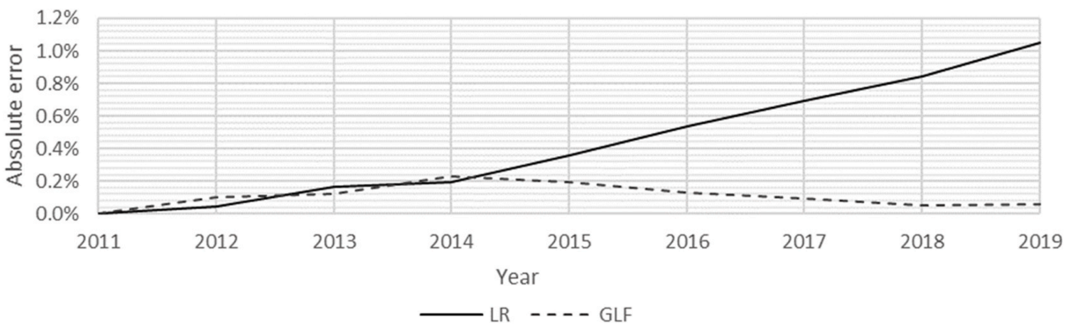

Fig. 4. Absolute error based on the total building stock demolition rate for linear regression (LR) and generalized logistic function (GLF).

Table 4
LR is the sum of all independent linear models, GLF is the sum of all independent GLF models, RMSE = root mean square error, R^2 = coefficient of determination.

	LR,RMSE	GLF,RMSE	LR,R^2	GLF,R^2
Overall for all residential buildings	0.043	0.046	0.067	0.040
Multifamily residential	0.057	0.024	0.207	0.124
Single family housing	0.073	0.020	0.026	0.177
Office buildings	0.132	0.051	0.053	0.616
Agricultural buildings	0.118	0.145	0.007	0.299
Average	0.085	0.057	0.072	0.251

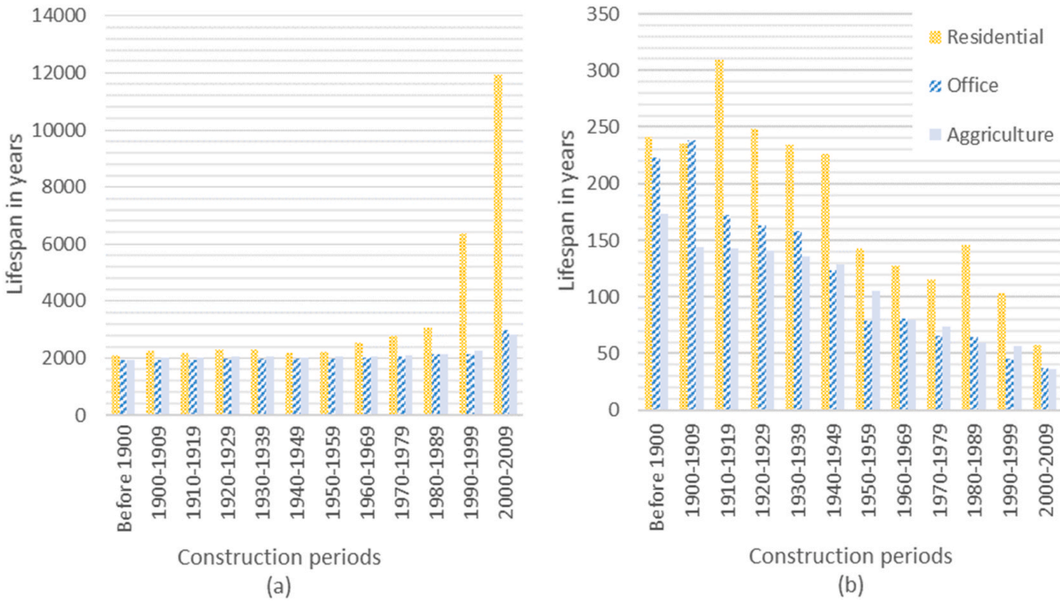

Fig. 5. Predicted lifespans of buildings constructed in specific periods, (a) linear regression, (b) logistic regression.

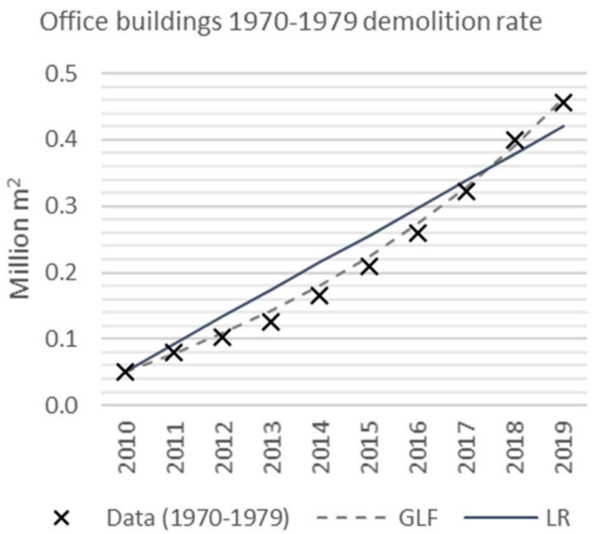

Fig. 6. The data show the accumulated demolition in mio sqm office buildings. LR is the best fit linear model, GLF is the best fit generalized logistic model.

push the lower boundary further down and are not captured by the logistic or linear models.

Consequently, building lifespans are likely to be even shorter than the lower boundary expectations if a circular economy creates market incentives to repurpose building materials and components. As such, the likelihood of an expected change to the demolition

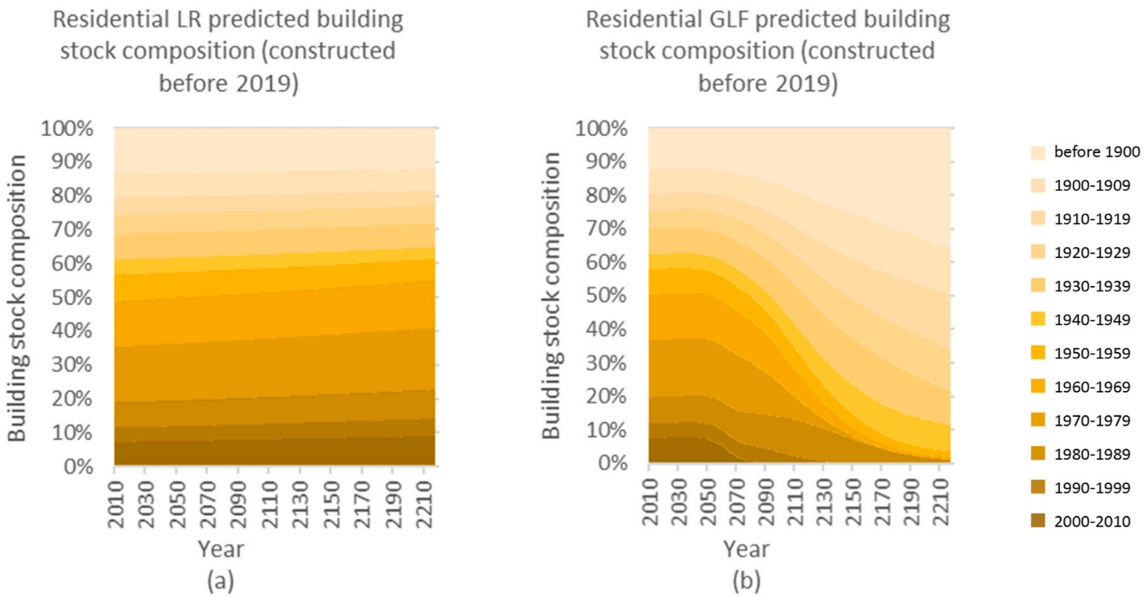

Fig. 7. Change in building-stock area composition of existing residential buildings from 2010 to 2210: (a) best fit linear model, (b) best fit generalized logistic model.

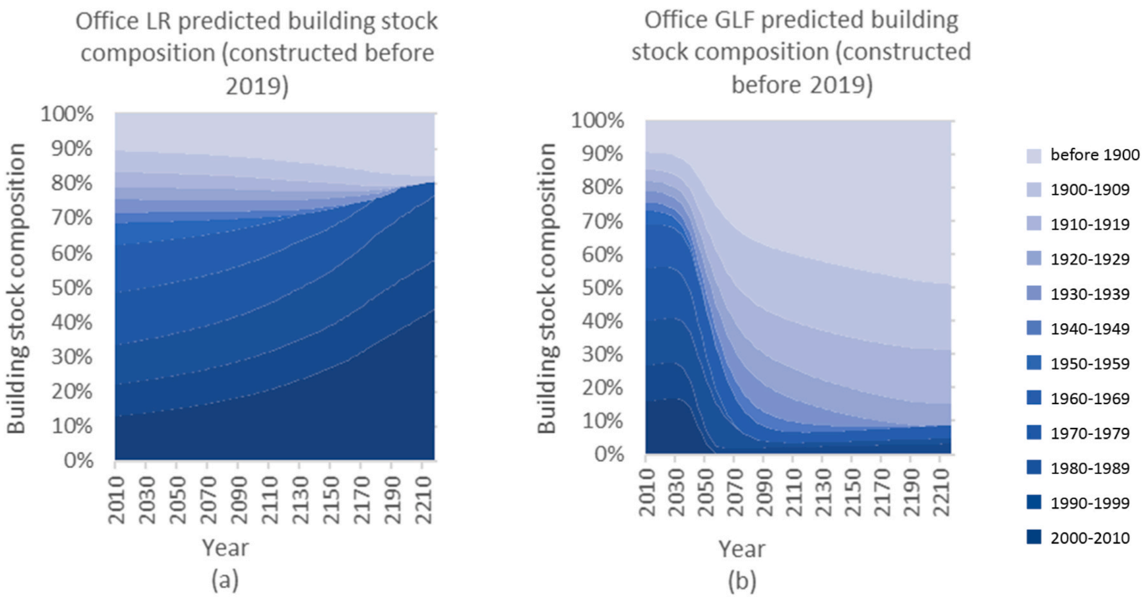

Fig. 8. Change in building stock area composition of existing office buildings from 2010 to 2210: (a) best fit linear model, (b) best fit generalized logistic model.

rate over time is higher than no change, and the lower boundary of the demolition rate (or building material release rate) peaks for residential typologies in 2060 and 2090 respectively, as shown in Fig. 10. The expected amount of demolition (or building waste release rate) is up to 5.1 mio sqm per year for residential buildings, not including buildings constructed after 2019. Confirmation of the demolition rate development of any typology is made simple to perform by collecting and comparing future data of $D(t)$, demolished square meters at each year t, with the weighted LR/GLF-model as shown in Fig. 10.

While the nonlinear logistic model better explains the current tendencies, changes to future building stock are not considered by the two models shown in this paper. For instance, changes in population size and living standards are not explicitly modelled. It is unlikely that Denmark will see a continuous increase in building stock at the same rate over the next 200 years, given its declining birth rate. New constructions and extensions are closely linked to population, BNP and market growth, which the models do not capture. The results shown focus on demolition tendencies based on building construction year and typology, but we may yet to see the consequence of a declining population in the demolition data. The predictive results are thus only valid in conditions of similar growth and progress as seen in the past 120+ years.

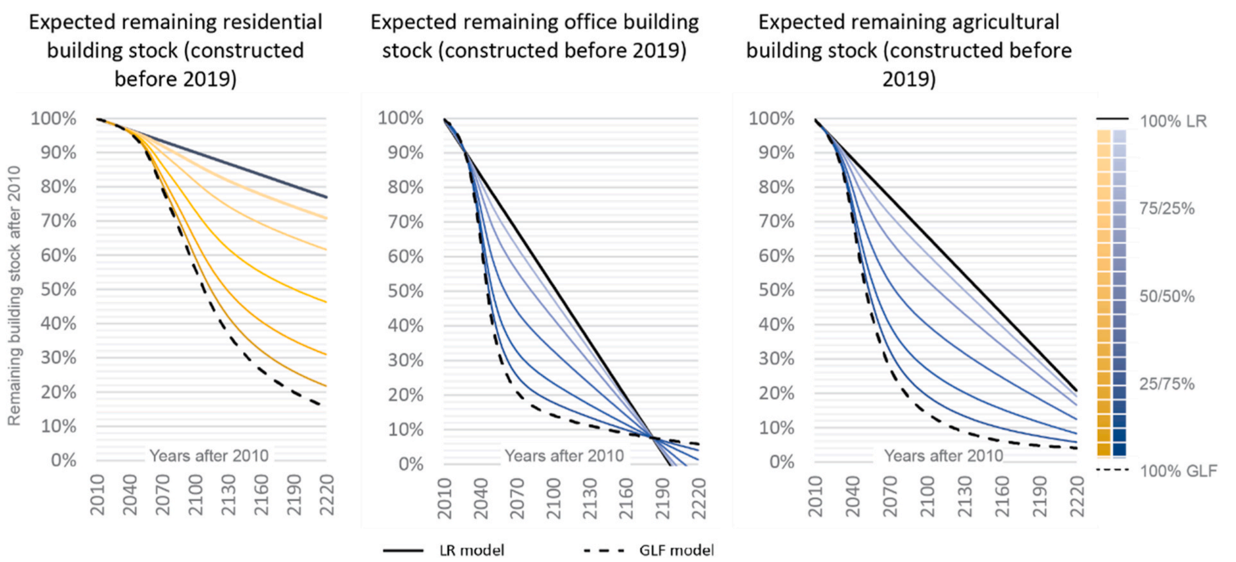

Fig. 9. Expectations of remaining future area of the building stock separated into residential, office and agricultural building typologies. LR is the best fit linear model, GLF is the best fit generalized logistic model, and possible variations are shown in between.

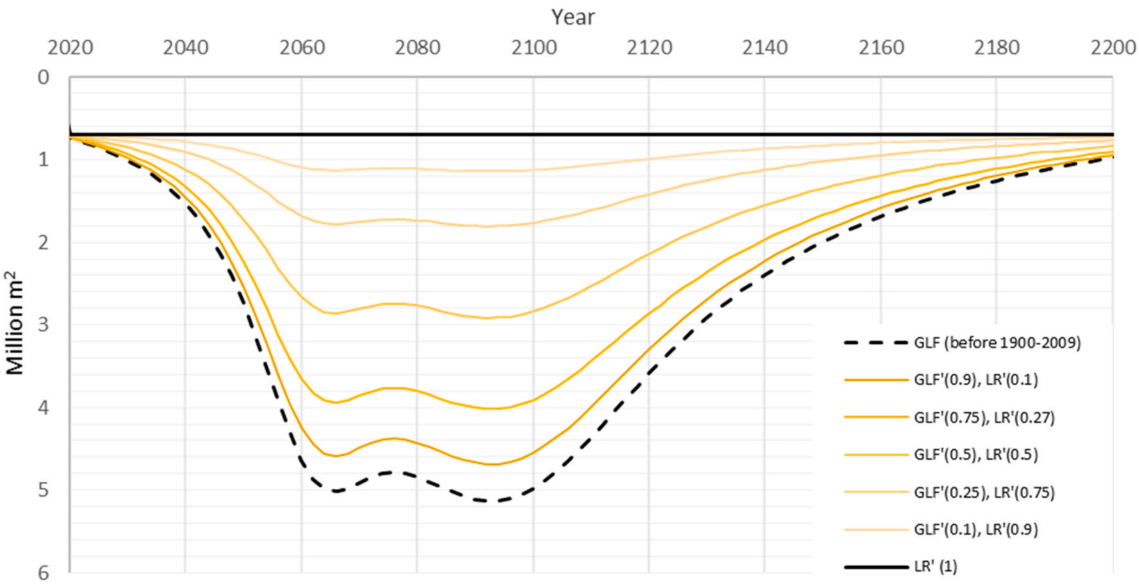

Fig. 10. Scenarios for annual demolished square meters of residential buildings constructed before 2010. LR is the best fit linear model, GLF is the best fit generalized logistic model, and possible variations are shown in between.

3.5. Assumptions and limitations

As shown in Fig. 2, the large increase in the total area in the dataset from 2017 was due to the better identification of unregistered buildings in the BBR. As such, the dataset for existing buildings was modified to include the known buildings from previous years and certain newly built extensions of existing building and demolished buildings post-2017, thus ignoring buildings that may not previously have been registered. As a consequence, older buildings are more likely not to be registered, which may result in marginally longer lifespans for very old buildings. Newer buildings are less prone to be affected by this modification of the raw data.

Linear fitted data against R2 are not affected by false local minima, as least squares ignores any local change of slope; this is in contrast to the logistic function model used. In the GLF approach, two open variables δ and t_0 are fitted to the dataset using simulated annealing. As an end result, local minima can affect the outcome of the best fit δ and t_0. In essence, there is a chance for multiple solutions to the average lifespan $\bar{t}$, and only one is presented. To minimize false optima, batches of 25-dimensional drift rates are used for each optimization, guaranteeing 10^4 tested solutions. Nonetheless, fits also occur near the upper asymptote. However, all these solutions have lower R2 scores, meaning chance in none of the analyzed periods and typologies has declining demolition rates. In determining the best fit GLF, several other tests were made where variations of ξ (see eq. (7)) gave similar and, in some cases, better fitting results. To limit the search space, it was decided to use the standard logistic case $\xi = 1$, where the progression and regression of cumulative demolitions have an identical but mirrored slope. It is worth noting that the derivative of the GLF model can take the form of a Weibull distribution with $k > 1$, which is consistent with the findings of [19]. In future works, other non-symmetrical versions of GLF may give rise to better predictions of the average building lifespan. Here one must note that the inflection point does not equal $\bar{t}$ as the case is for the symmetrical probability density function of GLF.

3.6. Implications and outlooks

Our results show that the lifespan of existing buildings varies significantly over different construction periods and typologies. In addition, the study show that the expected lifespan is much lower for new buildings than for older buildings. One interpretation of this effect is that old buildings that were at risk of demolition have historically already been demolished. The remaining buildings have historical, cultural or technical qualities that reduce the risk of destruction, thereby giving them a longer lifespan despite their already high age. This means that the socio-cultural aspects of the perceived value of buildings, if any, is biased towards older buildings compared to new ones, which affects the lifespan of the buildings of particular periods. A clear preference for preserving multifamily residential buildings from 1910 to 1940 can be seen in Fig. 11. This means that some typologies need less regulation for protection than others. The lifespans in this study are likely represent the northern part of Europe, which contains many similar building typologies [42]. In Asia and America, the lifespan of buildings is generally shorter ([12,16–18]), but similar predictive models can be applied.

When comparing the predicted lifespan of all buildings (column 2, Table 5) with the measured lifespan of demolished buildings alone (column 2, Table 5), the result show that the actual average lifespan is between 12% and 44% longer. This means that most previous results in other studies that only consider demolition data in a vacuum may have similar longer building lifespans when the entire building stock is taken into account. Comparing the result from Ref. [29], we see similar tendencies, except that our data show longer average lifespans. Since the dataset is about six times larger and lifespans twice the duration, notable differences in averages are to be expected. The GLF predicted lifespan in this study remedies the limitation of the selection bias when looking for buildings demolished in a rather narrow time window. When comparing "new" buildings built within the last thirty years (column 1, Table 5) to all buildings (column 2, Table 5), the model shows a significant decrease in lifespan expectancy. On average, the newest buildings last 45% shorter than older buildings (mean of all those built before 2010). This tendency is also seen in Serbia, Montenegro and Albania [19], albeit not as strongly as in the Danish data. Lastly, when comparing the standard lifespan with the predicted lifespans for old and new buildings, the results shows two important scenarios. When planning for new buildings such as residential buildings, it is to be expected that the median lifespan of a single-family house will be 36% shorter than the current standard and for multi-family dwellings 40% longer. New offices should expect a 50% shorter lifespan than that currently used as standard. For renovation purposes, it is more accurate to use the lifespans shown in column 2 in Table 5. Alternatively, when the exact period of construction is known, the results shown in Fig. 11 can be applied. For instance, multifamily residential houses reach nearly twice the expected age before demolition compared to current standard assumptions.

This study has focused mainly on existing buildings up to 2010, because the data availability for the newest buildings is very limited. However, it can to some degree be assumed that newer buildings built after 2010 are typologically very comparable to buildings constructed in 1990–2009, which means that similar lifespans can be expected. For newer office buildings, the average lifespan for demolished buildings was 61 years, which is 19 years below the normal life expectancy for office buildings used in Denmark [20]. When considering the average lifespan of all construction periods of offices, the lifespan was thirteen years longer than the standard lifespan. Again, there was a large spread in the expected lifespan over the construction periods where only office buildings built before 1960 could be expected to have more than eighty years remaining lifespan. In contrast, on average newer office buildings

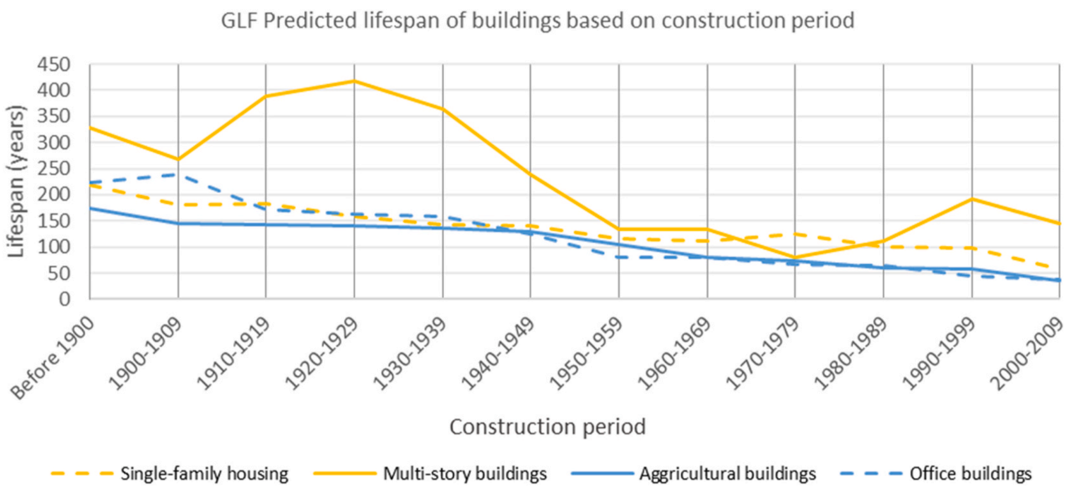

Fig. 11. Predicted lifespan of existing buildings based on their construction period.

Table 5
Lifespan of buildings. GLF predicted for the entire remaining building stock and for demolished buildings only based on a selection of periods and typologies.

Average lifespan/typology	1. Lifespan prediction, buildings from 1990 to 2010	2. Lifespan prediction (all periods)	3. Average lifespan for demolished buildings	4. Danish standard building lifespan [20]
Overall for all residential categories	81	168	98	120
Single-family houses	77	129	99	120
Multifamily residential	168	227	93	120
Agriculture	47	92	82	40
Office, trade and warehouse	41	93	61	80

constructed after 1990 have an expected lifespan of around forty years – half the standard lifespan [20]. This wide variety of possible lifespans is scientifically problematic, and more precise definitions of useful lifespans for LCA and LCC are needed.

The lifespan of most buildings is significantly shorter than what earlier studies have shown. Building components with a long lifespan have a significant environmental impact at the beginning of the building's service life and will not realize their full environmental potential if the building is demolished much earlier than the maximum lifespan of the building itself. Concrete, for example, has a very large environmental impact in production. However, because it has a very long service life, the environmental impact becomes smaller over time, especially because no replacements have to be made over the building's service life, which is the great benefit of materials with a long lifespan. The model show that new buildings have a significantly shorter lifespan, which may mean we have to rethink how we best design buildings with a long lifespan. Perhaps it is time for us to change our focus from extending the life of components to extending the life of buildings to ensure the greatest possible environmental benefit from our sustainable design strategies.

This study has focused on the lifespan of the existing building stock, but since this remaining lifespan can be increased through renovations or with political initiatives to reduce the amount of demolition, more studies are needed to examine how different types of renovation impact on the lifespan of existing buildings. Furthermore, demolition trends vary between low- and high-density populated areas [43], which also can have a impact on the lifespan. The study only examines building-related parameters such as year of construction and building use without taking the geographical context into account, but studies of demolition [17] have shown that there are many area-specific parameters that have a great influence on whether a building is demolished or not. Better lifespan predictions based on geographical, social and economic contexts could lead to more precise predictions of lifespans. Considering any change in policies and the future demand for new buildings, we see the importance of a continuing review of the demolition data.

4. Conclusion

This study has evaluated how we can assess and calculate building lifespans for existing building typologies. To this end, a generalized logistic model for predicting lifespans for existing building typologies was developed. A comprehensive database of more than 100,000 cases of demolition in Denmark shows apparent correlations between construction period and typology. The results show nonlinear changes in the demolition rate over time. With high confidence, it is possible to model the accumulated demolition rate with a generalized logistic model. This model is used to predict the remaining lifespans of existing buildings in Denmark built before 2011. The key findings from this are that office buildings generally have much shorter expected lifespans than previously assumed, and that multi-family housing has nearly twice the lifespan of single-family housing. However, residential buildings have longer lifespans than previous expectations have assumed. The results show a tendency for a declining lifespan based on the considered construction period, in which the lifespans of newer buildings (no more than thirty years old) are 45% shorter than the average lifespan. These results greatly impact on both the LCA and LCC of buildings, since the lifespan of most buildings proves to be significantly shorter than earlier studies have shown.

Author contributions

Rune Andersen: Conceptualization, Methodology, Data Curation, Formal analysis, Writing – Original Draft and review. **Kristoffer Negendahl:** Conceptualization, Methodology, Formal analysis, Software, Visualization, Writing – Original Draft and review.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rune Andersen reports financial support was provided by Horizon 2020.

Data availability

The authors do not have permission to share data.

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