Tightening the Circular Economy Model by Utilization of BIM at Early Stages of Building Projects

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Synopsis:

This master thesis investigates implementation of Circular Economy (CE) within the construction industry and its combination with Building Information Modelling (BIM) techniques. The research follows the problem-based methodology, while literature review and interviews are means of qualitative data collection on which the solution is built. The analyzed data resulted in five pillars that shape the solution.

The solution, in form of a process map, is a proposed new standardized workflow for circular building projects. Furthermore, various elements of the workflow, fx. material banks and phase transition assessments are elaborated on to provide technical understanding of the solution. The results of the newly specified processes allow for efficient actor collaboration, smooth transitions between phases, and standard facilitation; all with BIM & CE as outset.

I. PREFACE

This master's thesis project is written by three students as a compulsory subject of the 4th semester of MSc in Construction Management and Building Informatics program at Aalborg University.

The authors would like to thank the two supervisors of this project, Associate Professor Kjeld Svidt and Assistant Professor Ekaterina Petrova, for providing us with guidance and their expertise throughout the course of this project.

Special recognition goes to the interviewee participants who were able to take the time to answer our questions and share their experience within the field and, therefore, contribute to the solution of this report.

II. ABSTRACT

The building sector is one of the most polluting and waste generating industries, therefore, transitioning from wasteful to environmentally friendly economy models is urgent. While the research showing the necessity and benefits of implementing Circular Economy (CE) coupled with Building Information Modelling (BIM) to building projects has gained a lot of traction in the last few years, wide scale industry adoption is far from it. This thesis paper sets out to find lacks in the practices and workflows regarding circularity and to identify the state-of-the-art BIM tools with potential to support the processes. A systematic literature review and interviews with industry professionals are the basis of deriving five main pillars (CE knowledge, BIM expertise, collaboration techniques, early design, and standardization) to support implementation of BIM-based CE practices. The solution is in a form of a process map, which describes a new proposed workflow for early design phases, pushing building projects towards circularity. Important points of the workflow, such as Material Bank (MB) for existing and new buildings, and transitions between design phases are further elaborated on. The outcome and contribution of this research is a standardized project approach that facilitates effective collaboration and knowledge management by integrating BIM and CE model.

Keywords: construction industry, Circular Economy, Building Information Modelling, early design, standardization, collaborative framework

III. READER'S GUIDE & GLOSSARY

The structure of the thesis report document is shown in the table below:

CHAPTER	CONTENT
Chapter 1: Introduction	Problem field of the research area and project aim
Chapter 2: Background	Definitions and explanations of base topics for the remainder of the report
Chapter 3: Methodology	Research design, methods
Chapter 4: Literature Review	Review of relevant research contributions
Chapter 5: Problem Formulation	Formulated problem statement and sub-sequent problem questions
Chapter 6: Interview Analysis	Explanation and analysis of interviews with industry professionals
Chapter 7: Proposed Solution	Suggested solution to the problem formulation built upon the analysis of interviews and reviewed literature
Chapter 8: Future Development	Limitations of the solution and the future work to solve them
Chapter 9: Conclusion	Answers to problems raised in the problem formulation chapter

Table 1 Structure of the thesis report

The following acronyms are used throughout the document:

AEC - The Architecture, Engineering and Construction

BIM – Building Information Modeling

BAMB – Buildings as Material Banks

BO – Building Owner

BREEAM - Building Research Establishment Environmental Assessment Method

BoL – Beginning of Life

CEGPA – Circular Economy Gateway Phase Assessment

CE – Circular Economy

CEN - The European Committee for Standardization

CBM – Circular Business Model

CDW – Construction and Demolition Waste

DfD – Design for Deconstruction

DGNB – German Sustainability Building Council

EPD – Environmental Product Declaration

EU – European Union

EoL – End of Life

GHS – Greenhouse Gas

GDP - Gross Domestic Product

IFC – Industry Foundation Class

IE – Industrial Ecology

ICT – Information and Communications Technology

ISO - International Organization for Standardization

LCA – Life Cycle Analysis

LC – Life Cycle

LCC – Life Cycle Costing

LCCE – Life Cycle Emissions

LEED - Leadership in Energy and Environmental Design

MSDS – Material Safety Datasheets

MP – Material Passport

MB – Material Bank

MC – Main Contractor

MoL – Middle of Life

NPV – Net Present Value

PEPG – Project Execution Planning Guidelines

PLM – Product Lifecycle Management

RFID – Radio Frequency Identification

TC – Trade Contractor

TKC – Turn-key Contractor

XML – Extensive Markup Language

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CHAPTER:

1. INTRODUCTION

This chapter introduces the research project by explaining why the research area is interesting, what the problem is, what has been done (within academia, research, industry, and governments) and finally what the project aims are and the potentials of its integration.

With the global population on the rise, natural resources approaching depletion and greenhouse gas (GHS) emission constantly at high levels, many industries are looking for sustainable solutions. The building sector is very important to the economic growth with 9% of the European gross domestic product (GDP), 18 million jobs, and 3,1 million enterprises (European Committee for Standardization - CEN, 2019), but also it is one of the biggest polluters. The construction industry is especially in the spotlight for changes as it uses about 50% of raw materials taken from the earth and generates about 40% of all GHS emissions in Europe (European Committee for Standardization - CEN, 2019). These numbers are a result of traditional linear economy model of production and consumption, where resources are extracted, used, and then discarded when no longer serving a purpose. According to the United Nations Environment Programme, (2019) shifting to sustainable processes could bring reductions of over 16 gigatons of CO2 equivalent each year by 2050 in a building sector alone. Wastefulness in the built environment is recorded along the entire life cycle of buildings as 10-15% of building material is wasted during construction, 60% of European offices are unused during working hours, and 54% of materials landfilled after demolition (Ellen MacArthur Foundation, 2015).

The Circular Economy (CE) economic model emerged to remodel this outdated 'cradle-to-grave' thinking, where *''the value of products and materials is maintained for as long as possible; waste and resource use are minimized, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value"* (European Commission, 2015a). It has widely spread through research and academia, and it is now being recognized within governmental and organizational institutions, however the construction industry lacks wide-scale adoption, that only reaches isolation, either within a particular sector or project (Adams et al., 2017). It is struggling to adopt the CE model coupled with state-of-the-art technologies like Building Information Modelling (BIM) and environmentally sustainable methodologies because the role of managing and applying circular innovation in the built environment is often neglected (Munaro et al., 2020).

Implementation of CE models to buildings is problematic due to various reasons; the European Commission, (2020) lists the following potential barriers: structural resistance versus easy to disassemble, longevity versus flexibility, simple versus composite products, renovations versus new-build; while many fellow researchers discuss social, economic, and collaborative issues (Høibye and Sand, 2018; Leising et al., 2018; Van den Berg et al., 2019). The circular approach is inherently systemic and holistic in nature (Munaro et al., 2020), while the standard building project life cycle is commonly split into different project phases that are essentially working independently towards a common goal. The phases of a construction project performed by different stakeholders create short-term and incomplete links in the loop, defying the concept of enclosed holistic loop of material and resource usage by insufficient congruence, collaboration and information exchange (Van den Berg et al., 2019). Although the different stages are constantly being optimized for sustainability, the innovation happens without many considerations of the works of other stakeholders down the line of a project. To ensure more sustainable designs, various rating and assessment systems have been developed and implemented to use (Kylili et al., 2016). However, they do not rate the circularity of buildings (Leising et al., 2018) and are reactive measures, resulting reciprocal tasks for the design team to achieve the most sustainable alternative (Jalaei et al., 2020).

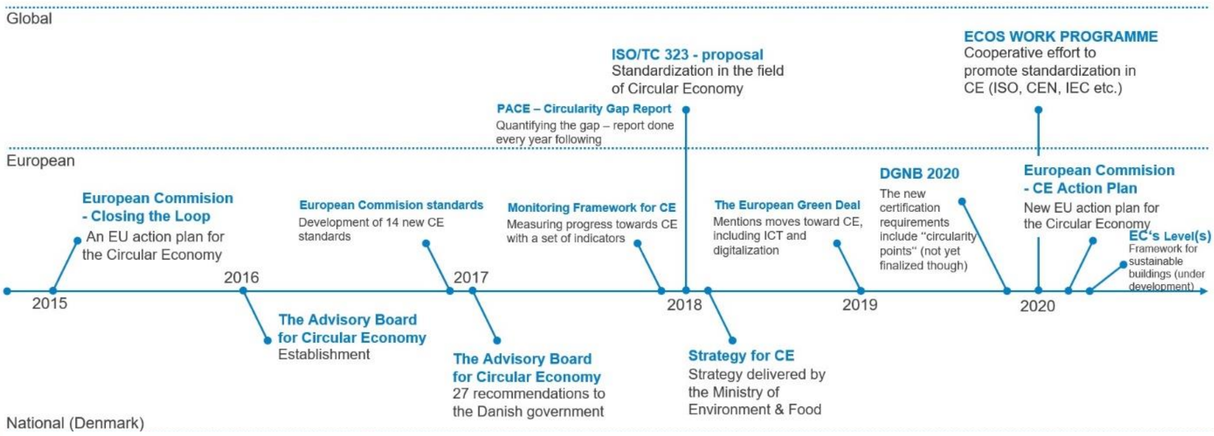


Figure 1 Excerpt of governmental CE initiatives in the last 5 years (own illustration based on references below)

At governmental levels, number of action plans, including construction industry guidance, have been formulated and published recently (Figure 1) shows the timeline of the publications mentioned further in this paragraph). In 2015 The European Commission presented an action plan towards 'closing the loop' and specifically to construction industry guaranteed taking *''a series of actions to ensure recovery of valuable resources and adequate waste management in the construction and demolition sector, and to facilitate assessment of the environmental performance of buildings''* (European Commission, 2015b). The Advisory Board for Circular Economy (2017) provided 27 recommendations to the Danish government, to boost the transformation towards CE, where four of them were directly specified changes in construction. In 2018 The European Commission introduced a monitoring framework, ensuring through a set of indicators, that best CE practices are in place. It is a continuously updated tool to follow key trends in the transition, to assess whether measures in place and the engagement of all the actors have been sufficiently effective (European Commission, 2018). Later that year the International Organization for

Standardization (ISO) has, together with its member bodies, proposed a new standardization in CE, which is still under development to this day. European Commission's 2019 report on the progress of the 2015 action plan was concluded as successful, stating that it has accelerated the transition towards CE in Europe. In 2020 the European Commission came with an updated action plan building on the foundation of the previous. Together with other key actions, it presented a future launch of 'Strategy for a Sustainable Built Environment' addressing the relevant policy areas like climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalization, and skills. Furthermore, the new action plan displays circularity principles for the construction industry and concludes with necessity of stakeholder cooperation at EU, national, regional and international levels to ensure systemic, deep and transformative transition to the CE (European Commission, 2020b).

The scholarly works regarding CE in the building sector have been booming last few years as reviewed per Munaro et al., (2020), however, despite ongoing development of 14 new CE standards at the European governmental level (Dansk Standard, 2017), Eberhardt et al. (2020) indicate lack of relationship between research and practice in the industry. The academia has recognized the great potential of the CE models as an opportunity for an efficient move toward sustainable built environment, it has, however, many moving parts that are complex to combine in one. One of the base enablers for a circular project are buildings that serve as material banks (MBs), where materials in buildings scheduled for would be documented to be reused in projects at their launch. Honic et al., (2019) describes a semi-automatically generated, BIM-enabled material passport (MP) that would provide data. With radio frequency identification (RFID) tags and BIM systems, even existing (non-digitalized) buildings could be integrated in the MB and MP database, as shown by Copeland and Bilec (2020). With that in mind, majority of research suggests adjustment of the design practices to enable reuse of materials at the end of a building's life. Jalaei et al. (2020) incorporated the available information with assessment systems, proposing an application where sustainability assessment could be estimated at a very conceptual stage. Others like (Wu and Issa, 2015) and (Jayasinghe and Waldmann, 2020) coupled LCA assessment tools for circular approaches; Santos et al., (2020) further explore LCA and BIM integration; and Akbarieh et al., (2020) researches BIM based design for disassembly (DfD) and end of life (EoL) of buildings. Apart from this really small and limited excerpt of works, there is a plethora of cunning and innovative researches to enable CE in the construction industry. However, there is a lack of literature on the inherent systemic nature, integration materialization, and operation of circular value models and the role of managing and applying circular innovation in the built environment is missing (Munaro et al., 2020).

The construction industry needs to be brought forward to CE admission, through clear definition of collaboration and data exchange techniques to boost stakeholder involvement and strengthen facilitation of CE model usage within building projects. The change towards circularity business requires to focus on systemic thinking to understand the entire life cycle of the building and the construction value chain, involving better stakeholder integration (Zimmann et al., 2016). Currently there are no standardized processes and workflows that would enable circular design and ease the transition between project phases. The importance lies especially within the early phases as the operation and performance is ought to be embedded in the design processes (Zimmann et al., 2016). Therefore, present processes and workflows need to be redefined and possibly new actor roles and responsibilities are due. The Advisory Board for Circular Economy's, (2017) recommendations to the Danish government, include one that is directly urging for exploitation of the Denmark’s international leading position in digitalization and new technology. The usage of BIM, coupled with other supporting technologies, needs to serve as a platform and a base for any information exchange in a project, to ensure transparency for all involved stakeholders and optimize their collaborative methods.

Therefore, the aim of this research is to collect and analyze the state-of-the-art technologies and practices to combine in a BIM-based framework of defined workflows and actor roles in design phases of construction projects, to enhance the CE model within the industry. Integration of this in the construction projects could guide project workflows towards circular approaches facilitated by standards.

CHAPTER:

2. BACKGROUND

This chapter provides definitions and explanations to topics that are seen to be the base for the research and important for the reader to be familiar with. The subchapters, therefore, gives a general overview of CE and BIM, and their current status with respect to the construction industry.

2.1 AEC INDUSTRY

The involved actors and exact processes of construction projects may vary due to specifications of individual projects, contracts chosen, and simply project types. Therefore, it is impossible to describe a process and list actors that would represent every project carried out. However, to set a baseline that the thesis can be compared against, a typical European process based on (RIBA, 2020) is adopted (Figure 2). Below is a description of project phases from initial brief to use of building:

In stage 0, the client would prepare a detailed brief including his ideas and requirements, forming together a business case. The design team is not yet appointed; however, skills are defined to appoint a client team.

Stage 1 includes feasibility studies that are meant to confirm if a site is able to suite the client's needs. This stage would result in a project brief including project outcomes and spatial requirements; the project budget is agreed

In stage 2, information requirements are defined to form an architectural concept based on the project brief. The architectural concept includes strategic engineering and aligns to the cost plan and outline specifications.

The contractor team should be appointed by stage 3. Testing of the architectural concept through design studies and analysis is performed resulting in spatially coordinated design that should align to the cost plan,

In stage 4 all design information needed to start constructing the project is completed. This phase is about the development of architectural and engineering technical design. A detailed construction phase plan is defined in

The construction phase plan is carried out in stage 5 and site logistics are finalized. The construction is monitored through a construction program and the quality is reviewed continuously. This stage also includes the

Construction is finished in phase 6 and the building is handed over to the client. Handover happens under the plan for use strategy and includes initiating aftercare and seasonal commissioning.

In stage 7, the building is used, operated and maintained and a facilities management team is appointed.

Figure 2 Royal Institute of British Architects - project phases, (RIBA, 2020)

2.1.1 Contract options in the AEC industry

The procurement strategy has an impact on the organization of the project, therefore must be considered at the early stages. Among the others the procurement form influences the responsibility for Project Risks which might be very important in terms of introducing new CE workflows into the industry. Moreover, the involvement of the subcontractors in the design work is very often determined by the chosen contract option and what is even more important dictates the responsibility for the overall design (RIBA, 2020). The general impact and short introduction to the procurement strategies, is as follows:

- Traditional – Number of contractors are issued for tender; the winning contractor appoints subcontractors to conclude the design with requirement of pre- and post-Contract Design Programmes (specifies when the design information will be created). Requires very clear definition of information exchange between the Main Contractor and the subcontractors in terms of possible changes to the overall design. Therefor Change Control Protocols must be in place and followed.
- Design & Build 1 Stage – The main contractor (design manager or lead designer) prepares the Design Programme. The crucial aspect of this type of contract is the amount of detailed construction information required from the client's team to provide correct extent of work. Often that leads to production of the Final Specifications.
- Design & Build 2 Stage – Contractor appointed under a pre-contract agreement and the contractors design managers preppers the Design Programme. Special consideration goes to the moment of this information being produced – before or after signing the contract. More information in advance gives the client better overview but requires time and may lead to delays.
- Management Contract Construction Management – Maximizes the overlap of different stages (design-procurement- construction) allowing for early design of some crucial building systems. This procurement grants more integrated approach for the Design Programme by including both the Main Contractors design team and specific subcontractors. On the other hand, it requires a procurement programme to connect the Design and Construction Programme.
- Contractor-led – Contractor provide the design team to work out the concept design as proposals for tender. The concepts awarded with moving to the next stage are supplemented by Design Programme, the winning bidder moves on to finalize the

tendering with specific contract sum. The clients design team may review the information for fulfilment of the contract.

This procurement strategies are recognized in the AEC industry in the UK. For the sake of this study the Danish procurement will also be described and compared to the UK version in the attempt of finding the best circular procurement form for the construction projects. On the Danish market the contract forms are as follow:

- Main Contract – The Building Owner (BO) enters a contract with both the Main Contractor (MC) and the consultant of the project. The Main Contractor enters contract with specific subcontractors. General Conditions for building and construction works and supplies, (AB 18) is the legal basis for the contract.
- Trade by Trade Contract – The BO enters a contract with each Trade Contractor (TC) and the consultant. The TC makes a contract with individual trade contractors. General Conditions for building and construction works and supplies, (AB 18) serves as the legal basis.
- Turn-key Contract – The BO enters a contract with the Turnkey Contractor (TKC) and TKC makes a contract with all the specific subcontractors and possibly the consultant. General Conditions for design and build contracts, (ABT 18) serves as the legal basis for the contract.

All the procurement forms should comply with ABR 18 GENERAL CONDITIONS FOR CONSULTANCY SERVICES FOR BUILDING AND CONSTRUCTION WORKS. (“Byggeriets regler,” n.d.).

All of the described contract forms have one in common, the liability and requirements are shifting from BO to contractors depending on the chosen form, also the information flow channels might change but eventually all the stakeholders should be on the same page with knowledge on the project progress.

2.2 CIRCULAR ECONOMY

Circularity and cycles in systems have ancient roots and can be interpreted in various schools of thoughts throughout the history. The Circular Economy is a concept that can be traced under different names and definitions, however single inventor or date cannot be stated. According to Ellen MacArthur Foundation, (2013) a notable traction and momentum was first gained in 1970s when the efforts of academics, thinkers and businesses describing practical applications to economic systems and industrial processes have been recognized. Because of its complexity, various applicability, and constant development, there is no single definition of the term. One of many definitions comes from perhaps the most recognized organizations in the CE context, The Ellen MacArthur Foundation:

''A Circular Economy is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the 'take-make-waste' linear model, a circular economy is regenerative by design and aims to gradually decouple growth from the consumption of finite resources. After defining what an economy actually is, this learning path explores the nuances of the concept of a circular economy, including the difference between biological and technical materials, the different opportunities that exist to keep materials and products in use, and the history of the idea. Finally, the benefits of shifting from a linear to a circular economy are highlighted.'' (Ellen MacArthur Foundation, 2013)

The restorative model aims to optimize the resource usage yielding in environmental, economic, and societal value. Within these three categories of value creation, the European Parliament has listed a number of opportunities, such as: reduction of GHGs, increased competitiveness, innovation, job creation, and enhanced security of raw material supply (Bourguignon, 2016). The restorative design intends to keep a material in cascades, ideally forever and to shift the product nutrients from technical to biological, so they can be reintroduced to the biosphere sustainably or reused instead of extracting valuable raw materials. That is given because after going through number of loops, the biological materials can safely re-enter biosystem as they biodegrade, while the technical materials cannot; therefore, the need is to cycle these materials continuously, capturing their value. The biological (green) and technical (blue) nutrients in a cycle are visualized by cascades in Figure 3.

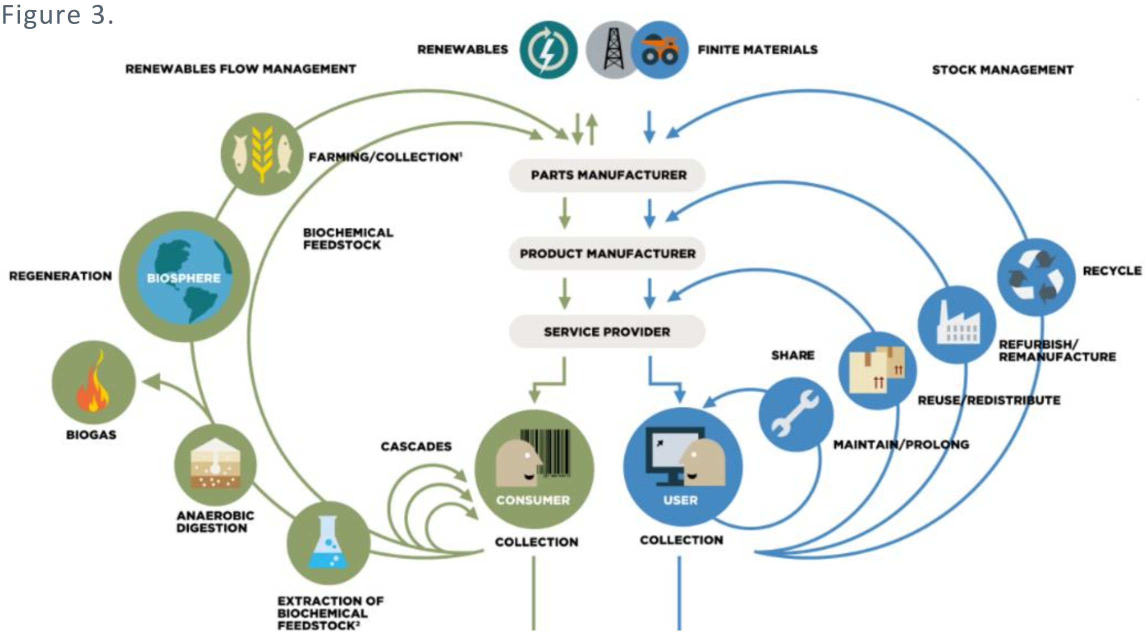


Figure 3 The Circular Economy System diagram (Ellen MacArthur Foundation, 2019)

2.2.1 Linear to Circular Model

During the industrial revolution of the world of the 18th century, where the global economy began transforming from agriculturally based to goods manufacturing, a linear model of resource usage of ''take-make-dispose'' was established and used ever since. In this pattern the raw materials are extracted from the Earth's crust, a production company applies energy to shape the material to its product, which is then used by the customers who then discard it when no longer needed. Such wasteful system in place is a result of lack of economic incentives to move away from it. Environmental aspects aside, this model was for many decades economically very viable for companies, however, with the population increasing and raw resources becoming scarcer and more difficult to extract, the market price of the resources has skyrocketed in the 21st century. As a reaction to this, companies try to make improvement in their products, making them more efficient, thus having longer life cycle and using less energy. However, this system is still focused on the product consumption, rather than its restorative opportunities, resulting in significant losses all along the value chain (Ellen MacArthur Foundation, 2013). Therefore, to be restorative in design, the companies apply a concept of eco-effectiveness to their products rather than finding a way to make them eco-efficient.

The key distinctions are explained in the definitions of the terms drafted from the Ellen MacArthur Foundation, (2013):

Eco-efficiency:

> It is based on presence of the ''linear'' model described in the previous chapter 2.2.1, ending in discarding of the products. Eco-efficient techniques allow to reduce the volume, velocity, and toxicity of the material flow system, but are incapable of altering its linear progression. Even though, some materials are recycled at the end-of-life, the products are never designed to be reused, which results in downcycling, i.e. downgrading in value and quality, rather than true recycling.

Eco-effectiveness:

> In comparison to eco-efficiency, eco-effectiveness does not try to minimize the ''cradle-to-grave'' flow, but to create a ''cradle-to-cradle'' cyclical environment, that allows upcycling, i.e. materials to be maintained as valuable resources and accumulate intelligence over time. This creates a synergy between economy and ecology. The eco-effectiveness concept

further lies within all principles of the Circular Economy model, transforming the linear flow to circular (Figure 4), which inherently reduces the necessity to extract materials (take).

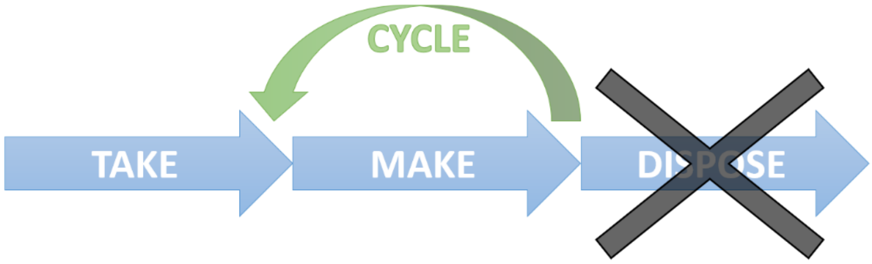


Figure 4 Shift from linear to circular economy (own illustration)

2.2.2 Main Principles

The Ellen MacArthur Foundation, (2013) has presented five main principals as pillars for the transition to Circular Economy, with the eco-effectiveness as sub-context in all.

Design out waste: Waste can be potentially non-existent when biological and technical nutrients of products are intended to be disassembled and reused.

Resilience through diversity: Diverse systems that are modular, versatile, and adaptable are more resilient to external factors, therefore more maximizing the flexibility and value.

Renewable energy sources: The consumed energy in its entirety should come from renewable sources.

Think in 'systems': It is crucial to understand the systemic connections and consequences of actions, whether it is within an industry or between industries.

Waste is food: Both technical and biological nutrients can be considered food for the following cycles if sourced and treated correctly. Biological nutrients to be reintroduced in the biosphere, while the technical nutrients to be upcycled.

2.3 BUILDING INFORMATION MODELLING

Similarly to CE, BIM has few different angles on defining the term, ISO 19650 standard defines BIM as *''Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions''* (Dansk Standard, 2018). As the definition suggests, BIM models do not only offer geometrical 3D (height, length, width) representation of a building and objects within, but they also (if created and specified sufficiently) include functional, topologic, and semantic attributes. For example, functional attributes can be installation durations or costs, semantic information store e.g. connectivity, aggregation, containment or intersection information and topologic attributes provide e.g. information about objects' locations, adjacency, coplanarity or perpendicularity (Volk et al., 2014). This can be further seen in how companies and actors view the value of BIM for their own use, where often only the digital model is used as a visual 3D representation with no intentions of sharing information further, portraying merely the

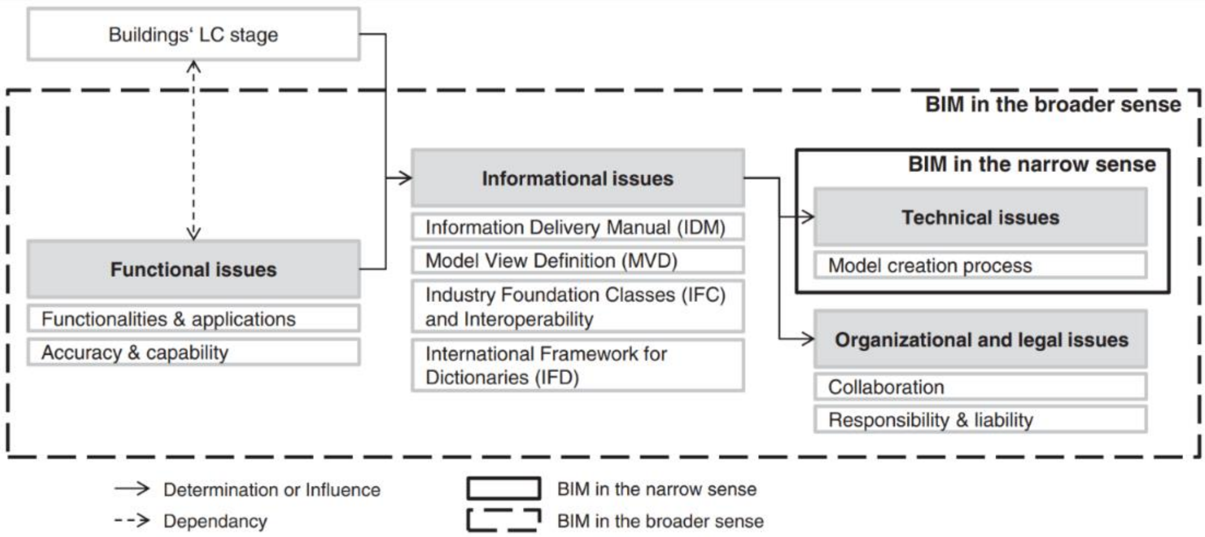


Figure 5 BIM in perspective of 'narrow' and 'broad' usage (Volk et al., 2014)

technical attributes ('narrow sense' in Figure 5). BIM incorporated as a platform, however, offers further collaborative and knowledge management advantages (extents of these depending on the vendor packages) carrying functional, information, organization, and legal attributes according to specific Life-Cycle (LC) stage ('broader sense' in Figure 5).

BIM features and tools are extensive, however, vendor specific in majority of cases. To increase the usability and accessibility of the digital data and to enhance the management and collaboration, BuildingSMART's openBIM comes in as an open standard collaborative process of sharing structured data, that is not vendor specific. BuildingSMART has developed a number of open-source file formats like IFC, BCF, gbXML etc. to support the processes, while IFC being by far the most used one (Jiang et al., 2019). That way collaborators may work in their preferred software, exporting to one of the vendor-neutral file formats, which's data remain usable. Furthermore, a notable part of BuildingSMART's work is the development of standards to support openBIM, like IFC, IDM, MVD, BCF, and bsDD standards to name the core five (BuildingSMART, n.d.).

STANDARD	GENERAL DESCRIPTION
IFC (Industry Foundation Classes)	Data export
IDM (Information Delivery Manual)	Description of processes
MVD (Model View Definition)	Technical requirements upon process description
BCF (BIM Collaboration Format)	Encoded information to allow workflow between different softwares
bsDD (buildingSMART Data Dictionary)	Definition of objects

Table 2 Brief description of five core openBIM standards

The main principles of openBIM are interoperability, openness, reliability, collaboration, flexibility, and sustainability that yield into assets in the building industry such as enhanced collaboration for project delivery, enhanced asset management, data access for the whole life-cycle, or extension of the breadth and depth of BIM deliverables (BuildingSMART, n.d.). BIM in general and openBIM as a standardized open process to enhance BIM have the features and potential to increase efficiency in collaborative processes.

2.4 CE & BIM IN THE AEC INDUSTRY

Significant traction in CE research and its application to build environment is noticed, however, wide-scale implementation in the industry is non-existent (Eberhardt et al., 2020a). The long lifespan is an inherent feature of the products (buildings, bridges, roads etc.) creating an unclear economic incentive for actors involved. This ties directly to the accustomed workflows in the industry, where projects are done by separate entities with separate individual goals. These phases performed by different stakeholders are naturally optimized over time, with regards to resources, time-management, and sustainability, however, without much consideration of the effects on prior or sub-sequent phases. This is referred to as 'silo-approach' which divides the professions into separate silos and tasks as a guild structure based on the specific craft productions and commercial practices (Rasmussen et al., 2017). This results in 'over-the-wall' syndrome where individual stages are done without full transparency to other involved parties and chosen information and data is passed on. (**Error! Reference source not found.**) This directly presents collaborative i ssues and loss of knowledge within the industry that need to be addressed. Both research papers by Svendsen & Tang, (2018) and Adams et al., (2017), supported by expert interviews, identify collaboration as the main challenge of moving towards CE in the AEC industry.

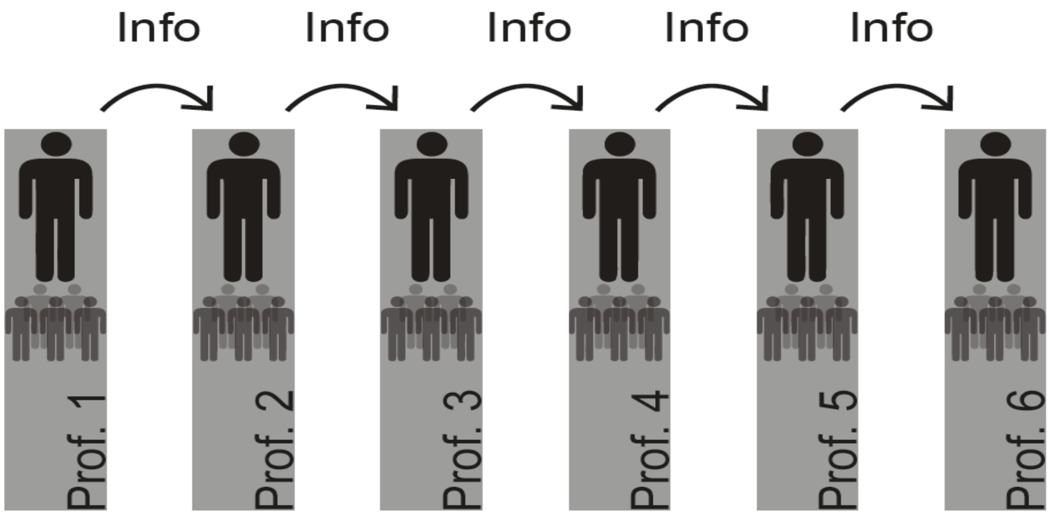


Figure 6 Silo-approach and 'over the wall' syndrome. Each silo represents a profession with a leader of the profession and related employees. The leaders are the once corresponding with each other. (Rasmussen et al., 2017)

Collaboration has been identified as a key requirement for progressing the circular economy and this should be explored within the procurement and supply chain management activities, as well as within the information sharing capabilities of BIM (Adams et al., 2017). Seemingly easily defined as 'working towards a common goal' the term collaboration within projects carries a lot of sub-topics, like knowledge management, planning, or communication - just to name a few. Therefore, digitalization using BIM that manages the broad topic of collaboration is seen to be a significant enabler and a necessity for circular projects (Copeland and Bilec, 2020).

2.4.1 Design for Deconstruction

Design for Deconstruction is not a new concept but the push towards sustainability, CE and digitalization moved it towards the design concept where the focus is on the assessment of the disassembly-ability of the load bearing components by implementing design processes enabling the reuse of these components in their original form (Akbarieh et al., 2020). The deconstruction part of the concept comes with opportunities of reducing the construction waste, better management of hazardous materials, supporting the reusability and, thus, preserving the resources and facilitating economic grow possibilities. There are also constraints e.g. additional time required for disassembly in compare to demolishing processes, space required for storage, lack of standards and possible supply-demand chains (Cai and Waldmann, 2019)

Design for Deconstruction in collaboration with BIM opens the path to the circularity of the design processes in terms of incorporating reusable materials and components from the early design stages (Akbarieh et al., 2020). Figure 7 displays the potential of circular project process of design and integration of MB, DfD and BIM in an approach towards promoting usage of reusable materials.

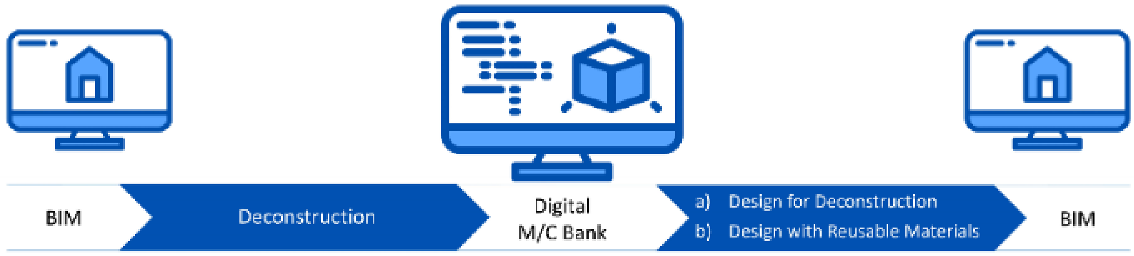


Figure 7 Circularity of materials with DfD and BIM (Akbarieh et al., 2020)

2.4.2 Material Passport

''Materials passports are (digital) sets of data describing defined characteristics of materials and components in products and systems that give them value for present use, recovery, and reuse. '' (Heinrich and Lang, 2019).

Material Passport is hardly a new concept, it was first introduced in Est Germany in 1982 and went through different phases until EU founded project Buildings as Material Banks (BAMB) started in 2016 with the aim of creating a common platform for MP (Luscuere and Mulhall, 2017). MP is identified by BAMB (Heinrich and Lang, 2019) as a main enabler of a circular shift in the AEC industry by allowing for easy access of information. The main goal of this concept is to:

- Support the choice of healthy and reusable materials in the design process.
- Add or keep value of materials/components over time.
- Support new supply chain methods and reverse logistics within the industry.
- Improve access to information for all the stakeholders.
- Enable circular potential of materials (MP itself does not make a material good for CE) by adding transparency to the actual ingredients of materials/components.

Material Passport aims to improve effectiveness of already existing environmental certificates like Environmental Product Declaration (EPD) and Material Safety Datasheets (MSDS) by shifting the focus from evaluating only hazards, toxicity, and environmental impact to resource productivity and reusability. Thus, there is a need of adding CE enhanced indicators that stakeholders of AEC projects could extract to evaluate CE aspects they see fit to focus on. The type of information required to accommodate this process will be described more detailed in chapter 7.3.

2.4.3 Material Banks

Material Bank concept is promoting buildings as repositories of high-quality materials ready for reuse in other projects through transfer of deconstructed materials or components (Cai and Waldmann, 2019) thus, the concept is very close related to CE principles. The MB enables the reusability the key business of the bank:

- Organizing demolition and deconstruction planning on the global scale.
- Providing certification of materials and improving the assessment of their quality and condition.
- Storing data on materials and components throughout the entire life cycle/cycles.
- Allowing data from the existing buildings to enter the bank.

These key trades secure that only reuse suitable materials and components are be used in new projects and provide an insurance in terms of crucial parameters e.g. residual load bearing capacity, ability to be re-assembled and potential ratio of degradation from previous life cycle. (Cai and Waldmann, 2019). The main responsibilities of the MB and the information flow between the existing and future buildings are visualized in Figure 8 where the existing buildings are divided into two categories: designed with BIM and without BIM (older structures). Since BIM enabled data is not available for the older structures, their evaluation is first performed in situ ad hoc during the deconstruction. Thus, the quality assessment business and the certification of materials and components are hindered.

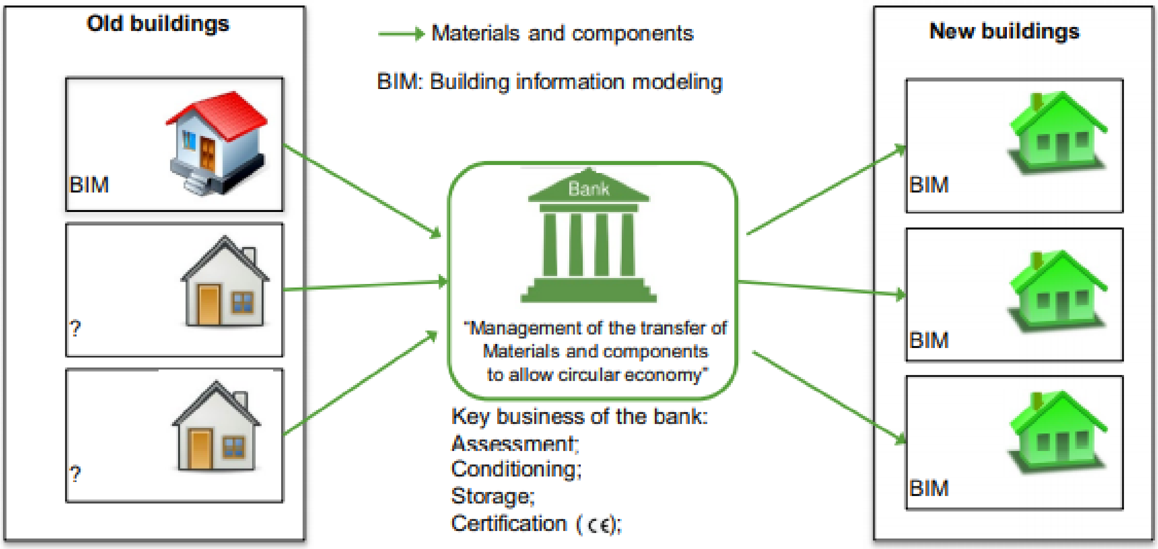


Figure 8 Information flow between old buildings, MB and BIM (Cai and Waldmann, 2019)

The information flow between MB and BIM is an important feature of a modern AEC industry to secure interoperability and constant update of data through the stages of the project and transfer of data after deconstruction processes to the new BIM model. Figure 9 displays the flow of information required for the MB and BIM to work together towards a data centered approach of circular projects.

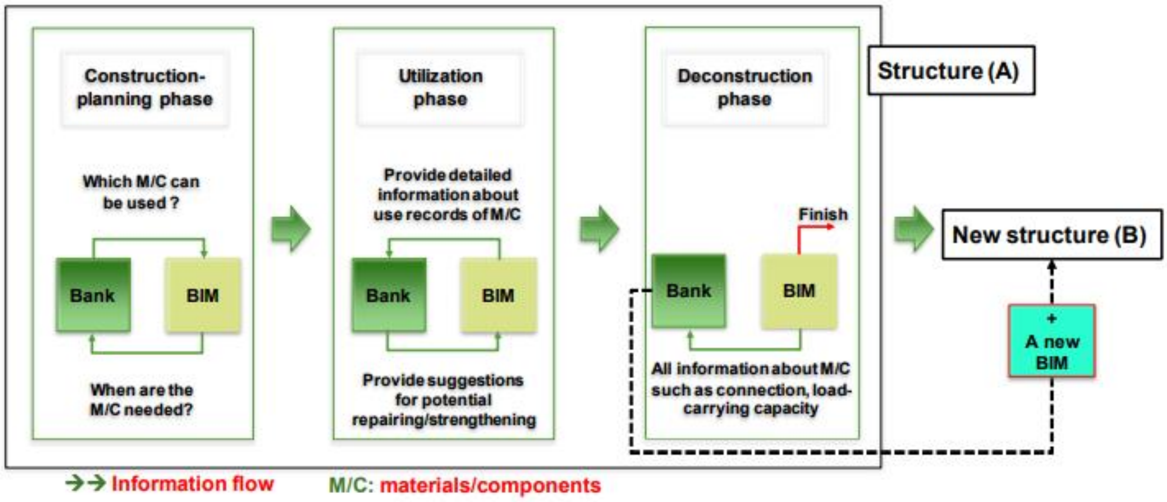


Figure 9 Data flow between BIM and MB (Cai and Waldmann, 2019)

CHAPTER:

3. METHODOLOGY

This chapter provides general descriptions of the research, data collection methods and means of analyzing the data to provide a foundation for understanding the general approach and to evaluate the reliability and validity of the research.

3.1 GENERAL CONSIDERATIONS

the methodology reflects the direction of the research, as final words of the introduction to this paper read:

The aim of this research is to collect and analyze the state-of-the-art technologies and practices to combine in a BIM-based framework of defined workflows and actor roles in design phases of construction projects, to enhance the CE model within the industry. Integration of this in the construction projects could guide project workflows towards circular approaches facilitated by standards.

Therefore, the research for data collection needs to include methods for gaining knowledge both on the current practices within companies but also the possibilities that are within academia to be implemented. The analysis of the qualitative data needs to be thorough, to combine the two aspects mentioned.

3.2 RESEARCH DESIGN

The specific methodology approach is chosen to determine the CE driven processes in AEC projects and the level of digitalization supporting this drive. Thus, BIM enhanced circularity is a priority of the research strategy for this study. The research strategy is based on the qualitative data accomplished through the systematic literature review (secondary data) and set of interviews (primary data) in form of combination of both inductive and deductive approach as described by Bryman (2012). Qualitative data collection is used in order to identify patterns emerging from the data acquired and because it grants flexibility and insight on how people understand and experience the surroundings (Macdonald et al., 2008). This approach is identified by the authors of this study as best for interpretation of indicators related to CE and BIM co-existence and patterns in the AEC industry.

3.3 DATA COLLECTION

Data collection is a critical process of research progression and therefore must follow an organized and well-planned strategy. Taking into consideration the aim of the study and to secure a high-quality of data required to gain insights on the research problem, the methods and procedures of data collection are conducted as follows.

3.3.1 Literature Review

In order to identify critical literature, this study takes an approach of a systematic literature review. This allows for better understanding of the overall picture of the issue and secures reliability of the findings, since the systematic review is characterized as objective, systematic and transparent (Siddaway et al., 2019). The assumption for the research was based on believe that BIM has a role to play in construction projects' impact on the environment and might support Circular Economy approach using tools available through the digitalization of the AEC industry. Thus, support better communication of the circular indicators by stakeholders and improve overview of the life cycle of the buildings. With the purpose of fulfilling the requirements of qualitative data collection as systematic literature review, the study adheres to the following steps:

- Scoping – after initial literature scoping the study takes aim on the issue of BIM co-existence with CE concept in the academic literature. Several options are discussed based on the available literature and common knowledge of the authors and the focus is on the BIM and LCA tools compatibility with implementation of circular projects in the AEC industry.
- Planning – Based on the general scope of the study search terms are established. The Inclusion and exclusion criteria for the literature search is agreed upon to eliminate studies not aligned with the scope:
- Inclusion – AEC related, English language, only the most relevant and up to date studies.
- Exclusion – BIM implementation focus.
- Identification – The search terms are used across two databases: Primo and Google Scholar.
- Screening – The search results are exported to the citation manager (Zotero) to remove possible duplicates and ease the process of research. At this stage the abstracts are examined based on inclusion and exclusion criteria.
- Eligibility – The full texts of chosen studies are assessed for sensitive information.

(The documentation of the research process is available in APPENDIX A.1 and A.2)

Full results of the research process for the literature review are represented by the PRISMA flow chart (see Figure 10 in Chapter 4. Literature Review)

3.3.2 Interviews

The interviews are performed as semi-structured to provide more in-depth understanding of interviewees' insights but at the same time follow a specific framework which allows to address key aspects by open manner questions rather than very specific ones. The open – ended responses mean the researchers can uncover additional problems and prospects (Bryman, 2012). The participants are chosen based on their current role in the circularity implementation in the AEC industry. Since the CE driven projects are not common, both the industry actors (Architects, Sustainability Consultants, BIM managers) and PhD students (Larsen, 2020) are invited to participate. It is worth to observe that some industrial PhD students comprised both the academic approach and professional experience within the construction project processes.

3.4 DATA ANALYSIS

The data analysis is executed as thematic analysis to achieve understanding, overview, and context of the interviews. The techniques of analysis follow the steps of familiarization, meaning coding, generating themes and defining and naming themes (Caulfield, 2019)

Familiarization is the first step towards analyzing the information. The interviews are transcribed which allows to get familiar with the text and this way enables the next steps of the analysis.

Meaning coding consist of coding and/or categorizing. Coding includes assigning one or many key words to a part of text for easier identification of a statement. Categorization requires more systematic approach to the conceptualization of a statement (Caulfield, 2019)and in context of this study is performed in form of themes supporting the coding.

The codes are initially clustered together to form a platform for uncovering the validity of the data and allow to better visualize the context of the information pursued by the authors. The process and effects of assigning codes and themes can be seen in

3.5 FEEDBACK SESSION

In order to validate the relevance and usability of the solution to the problem formulation, a feedback session is performed with 2 chosen professionals that also take part in the initial interviews as described in chapter 3.3.2 Interviews. The feedback session is organized as an open interview to gather any solution faults, recommendations, and suggestions from the industry professionals. Since the chosen interviewees are skilled mainly in sustainability/circular economy, the feedback session revolves mostly around circular economy aspects of the process map and the gateway assessment. The results of the session are taken into consideration for an improvement of the solution to the problem formulation and to help establish any possible future works.

CHAPTER:

4. LITERATURE REVIEW

This chapter provides terms and definitions that are used as a part of research to understand the perquisites and the aim of the study as systematic literature review of CE in AEC industry, LCA and LCC, sustainable assessment and collaboration tools.

Literature review is based on the following search terms to find relevant literature: "circular economy", "reuse", "design phases", "early design", "building materials", "material data collection", "circular buildings", "stakeholder collaboration", "life cycle", "BIM", "LCA", "assessment tools".

The search terms are then evaluated and updated with Boolean operators resulting in the following expression: (design phases OR circular economy) AND (building materials OR early design) AND (BIM AND material data collection) AND stakeholder collaboration

The literature search process including the definitions of the search engines is portrayed by a PRISMA Flow Chart below.

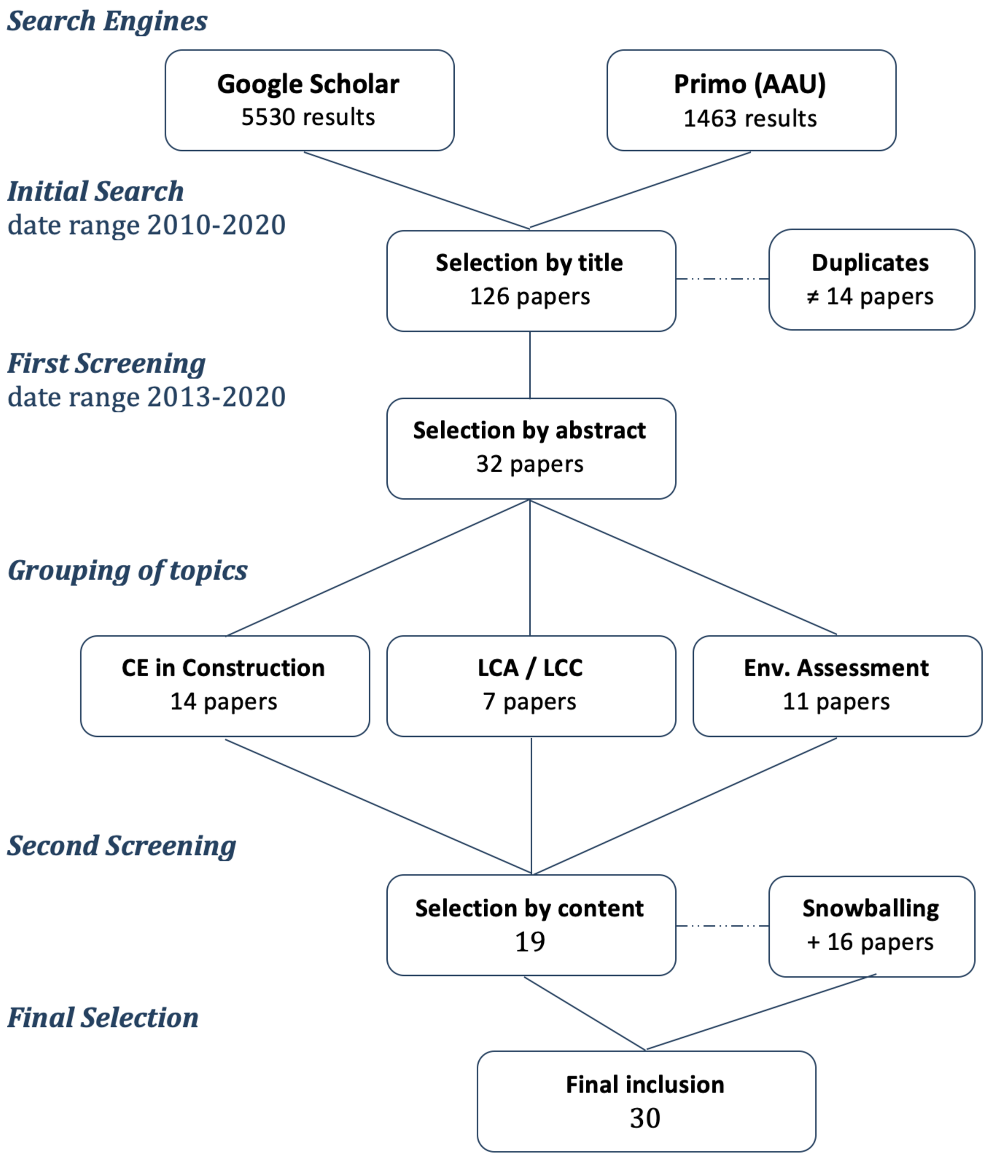


Figure 10 PRISMA Flow Chart (own illustration)

After performing the initial screening of the literature, three groups of research are defined in the literature review breakdown – these can be seen on Figure 11. The following research is performed based on these three categories.

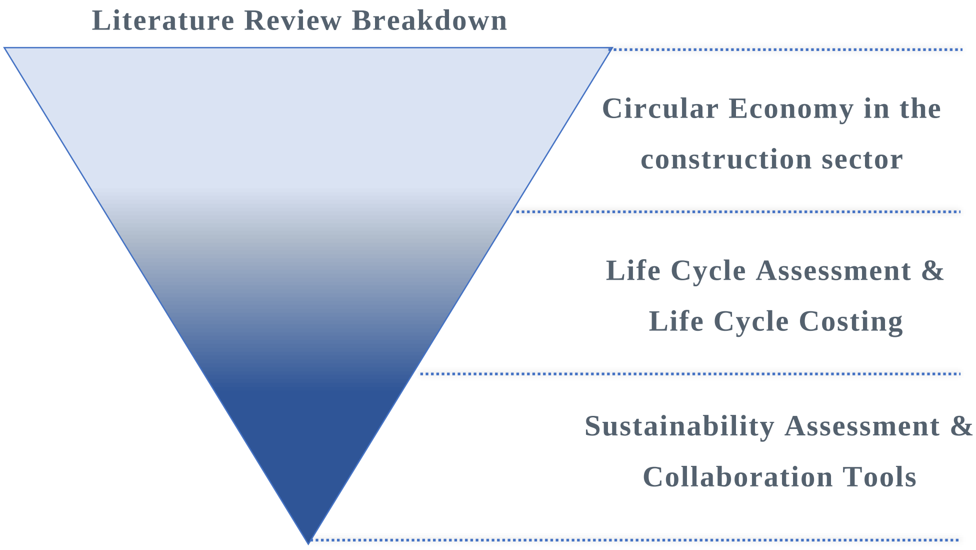


Figure 11 Literature Review Breakdown (own illustration)

4.1 CE & BIM IN THE AEC INDUSTRY

Pomponi and Moncaster (2017) claim that the AEC industry accounts for 25-40% of the world's total carbon emissions and is the biggest global consumer of raw materials (Forum, 2016) and suggest that emissions from the industry are to double by year 2050. Authors aim in their research to address a gap between the current focus on short-lived manufactured products and long-life building products which, when assembled, might not fit into the manufacturing logic. Pomponi and Moncaster investigate six dimensions for the research of circular economy including initiatives, approaches and ideas to move towards circular buildings. They define these six dimensions as governmental, economic, environmental, behavioral, societal, and technological and claim that these are a good basis for research of circular economy. The authors state in the conclusion of their work that future research could focus more on interdisciplinary practices and investigate technological and societal links within circular economy approaches. According to extensive interviews with 16 AEC actors performed by Høibye and Sand (2018) 32 policy instruments (information, regulations, economic incentives) are defined to boost transition towards CE in the construction sector. The interviewees mention, among others, the necessity of stricter requirements for the traceability and content of information or improvement of the responsibilities of contractors for circular practices.

The content and traceability of information stems from the design phase of the project where most decisions about building components and materials are taken. Therefore, circular economy plays a significant role already in the design stages. LCA as a tool that supports circular economy in evaluating environmental impacts of the building should therefore act not only as an assessment tool, but also as design support tool in the early stages of the project. Since information contents, upkeep and sharing are an important basis for all processes, stakeholder involvement within early stages (and during all phases of the project) should not be overlooked. Eberhardt et al. (2020) presents a systematic review of papers about CE and building design published from 2013-2019. The authors state that using non-reusable materials will lead to resource depletion. The reviewed literature is focused on the ‘’reuse’’ aspect of the CE principles. Environmental benefits of CE strategies are maximized by focusing on preventive strategies particularly during the early design stages. The study indicates possibility of a missing link between research and practice and pinpoints lack of studies describing how LCA can potentially improve the environmental performance of the building. That brings a risk of choosing wrong design strategies. Thus, the authors suggest further developing of a new design typology that structures and prioritizes the design and construction strategies (16 design strategies) by the most promising, for minimizing building-related environmental impacts. The authors suggest different design strategies for different buildings or materials based on how they are used (use cycles).

Munaro et al. (2020) says that the market for CE in the next 10 years will boost economic growth by up to 4%. There are many challenges that can occur in the attempts to move towards circular buildings. The authors underline stakeholders’ integration as one of the crucial aspects of CE implementation and lack of CE implementation in current business models and suitable practices among supply chain actors. The study promotes developing guidelines for CE implementation and choosing CE indicators already in the early stages based on LCA and material flow analysis. The authors claim that currently, most of the buildings are demolished with an average lifespan of only 20 years because they no longer meet the needs of their users and that the resource productivity will become a main focus in the construction industry in the near future. The study addresses the importance of overcoming the problems of insurance, guaranty and structural capacity of reusable materials but also government support and creation of new laws for CE implementation within the construction industry. van den Brink et al. (2017) underlines the lack of knowledge on how the construction processes will look like if the project implements CE. CE imposes suppliers to retain the ownership over their products, make to stock chains does not exist in the construction industry due to unique components for each project. The study proposes a new stakeholder within construction projects – Service provider or more specifically manufacturing SP offering three different kinds of services; base, intermediate, and advanced services. The study underlines difficulty in stating if the circular services would be as beneficial as normal services in general, this is since circular products need to be taken back at the end-of-life cycle. The study offers 5 service business models for the SP to choose from, depending on variables and services provided by the SP. Model 1 where the SP has all the competencies, and no external suppliers comes closest to the CE concept. The authors underline the ownership of individual components as one of the main problems due to legal issues. Financial uncertainty is also an issue in circular business models because they are dependent upon resource price levels (must be going up constantly).

Van den Berg et al. (2019) analyze circularity challenges in construction projects by following a school renovation project that aims to be done in a circular fashion. They argue that one of the root causes of the significant amounts of construction and demolition waste associated with the industry is the designers' traditional view of their creations being permanent and as a result, most buildings can poorly adapt to changing user needs. The numerous workshops and meetings where the researchers were present together with all the stakeholders showed clear differences in thinking of construction projects among different AEC actors. That is perhaps due to design professionals lacking systematic methodologies to help them implement circularity thinking. One methodology that can help stakeholders work in a structured and understandable manner is BIM. BIM can serve as a framework for different processes during the entire project run, defining standards, guidelines and needs and therefore can aid actors in circularity thinking. Jrade and Jalaei, (2013) address in their research that demand for sustainable buildings with low impacts on the environment is increasing and there is a need for adoption of new technologies such as BIM and collaboration of BIM with sustainability tools. The authors propose a framework utilizing an external database that is linked to BIM tools and includes information about building components. They suggest the use of Revit as a BIM tool, Excel as the external database that stores component information and Athena Impact Estimator which is a life cycle assessment tool evaluating the building's environmental impact. Jrade and Jalaei define a gap in the research – the external database can be very limited in terms of the variety of certified building components which can therefore limit the design creativity of new projects. Similarly to Jrade and Jalaei (2013), Aguiar et al., (2019) state that reuse of building components on a bigger scale has not been adopted mainly because of poor building information management – poor information about materials. The authors believe that BIM has a high power in moving buildings towards circular economy and that material passports that specify information about reused materials in implementation with BIM can lead towards sustainable building design. The authors' research specifies the process of generating different BIM model provided by different actors for different purposes. Aguiar, Vonk and Kamp suggest a new stakeholder role – the harvester, who is responsible for gathering information into the circular model that is adjusted to contain information relevant to material passports and is also responsible for the sharing of this model on the agreed upon data platform. Honic et al., (2019) define a lack of tools that allow assessment of recycling potential in the early design stages and thus suggest a BIM-based MP. Authors prove the concept of a semi-automated generation of a BIM-based MP and propose a data and stakeholder management framework to show responsibilities of the different parties. The authors suggest in their research the use of a new stakeholder role – the MP consultant within the AEC organization who is in charge of integrating recycling data and data acquired from LCA into the BIM processes. Copeland and Bilec, (2020) state that currently the AEC industry functions on a so-called "take, make, waste" model that portrays the operation of a linear economy, where virgin materials are used to make a product and disposed of as waste, which leads to resource exhaustion and emissions. Copeland and Bilec address this issue by creating a theoretical framework of Buldings as Material Banks in connection to a BIM system to accommodate for centralized data within the project. The authors mention that radio frequency identification (RFID) tags, amongst others, can be used to demonstrate the framework with the tag's data stored in a blockchain database. They claim that if information about building elements is sufficient and stored in an orderly manner with accessibility for all stakeholders and a database that can store data regardless of its nature, the move towards circular buildings should improve significantly. Di Biccari et al. (2019) also present the concept of BAMB. Their research states that CE in the literature is limited to waste prevention and material management and suggest the need for indicators of the CE implementation in the construction industry. The study proposes 5 Circular Business models (CBM) and shares the opinion of Ellen MacArthur foundation about the need for highlighting the value of CBM to all the stakeholders. The BAMB concept is recognized by the study as an encouraging solution for adoption of CE. BIM based optimization algorithm to find a trade-off between the LCC (life cycle costing) and LCCE (life cycle emissions). The study proposes an Autodesk Revit plug-in as a framework to analyze the level of circularity. The framework requires external database input for LCA and prices and specific knowledge on defining the activities for Work Breakdown Structure (WBS) for a specific CBM.

When discussing circular economy, the term ‘building life cycle’ cannot be avoided. Generally, there are three stages of the building’s life cycle – beginning of life (BoL), middle of life (MoL) and end of life (EoL). Velasquez et al., (2020) state that the implementation of circular economy requires modifications on all phases of buildings life cycle – redesigning the product in beginning of life, better maintenance in use in middle of life and avoiding disposal at end of life, while these modifications require conditions such as good stakeholder collaboration and information exchange, which could be improved by the use of Information and Communication Technology (eg. BIM). Whereas, Delgado and Oyedele (2020) study underlines the focus of researchers on only either beginning or the end of life cycle. The study recognizes the operational phase of construction projects as the largest share of total life cycle cost, therefor applying CE principles in this phase is crucial for minimizing the cost. The authors say fragmentation of the industry is the main obstacle for the CE implementation but also, standard data models (e.g. IFC) must be developed for the CE aspects because they have not been considered in the existing standards. Even though many existing entities of the IFC specifications already record data required for the CE aspects none of them are represented by these entities. The study underlines three methods for extending the capabilities of the IFC specification: (1) make use of proxy elements and user-defined property sets; (2) references to external data; and (3) extending the IFC schema (i.e. the data model). The authors recognize the 3rd option to guarantee the interoperability but with lengthy and official procedures. As opposed to the research by Velasquez et al.(2020) and Delgado and Oyedele (2020), Akbarieh et al. (2020) is focusing on the BIM based End-of-Lifecycle (EoL) of buildings and related with that Construction and Demolition Waste (CDW). The study promotes the material classification from the early stage of design as this will improve the waste segmentation and states that clear lines of personal/company responsibility are necessary for better CDW management due to social and culture attitudes of humans towards responsibility and blame shifting. Study describes different EoL scenarios designed by the use of BIM based case studies: disassembly of DfD-oriented components at the end of the first lifecycle, while concrete and steel are recycled at the end of the second lifecycle turns out to be the best sustainable option in terms of embodied energy, cost, transportation. The authors describe attempts to build BIM-based demolition waste estimation frameworks that is built upon the types of input construction materials. The study underlines the need of large digital data storage at the end of the life cycle, this could be reduced by using external material banks databases link to the BIM but should be decided upon already at the conceptual level of the project.

4.2 LIFE-CYCLE ANALYSIS TOOLS

Cambier et al., (2020) define existing categories of sustainability tools such as Design principles tools, Material flow analysis tools, LCA tools, Material and product labels, Reused material platforms, Material passport tools, LCC tools and Knowledge sharing platforms and, from the developers point of view, reveals opportunities to work on new design support tools and improve already existing tools within share-ability and transfer of information by different stakeholders. The authors propose a framework to guide actors to use appropriate tools per each design stage and per tool category and the needs per design per tool category. Cambier, Galle and De Temmerman suggest following from comparing tools and needs of stakeholders: improvements on current learning networks and platforms, need for clear workflow management and monitoring tools to share data in an efficient and understandable manner and need for more practice-oriented development of design support tools. As stated by Basbagill et al. (2013), a significant amount of the life cycle impacts of buildings can be traced back to decisions made in the early design phase of the project, therefore the choice of materials is crucial in this stage. Still to this day, many environmental performance assessments of these choices happen in the later project stages and any changes can lead to an increase in building impact. The paper mentions that building information management which is widely used for stakeholder collaboration in early design lacks interoperability with LCA resulting in a fragmented and uncoordinated processes. The authors propose a BIM-enabled decision support method that can be used to help predict decisions that can hinder building's impact with the results shown in an impact allocation scheme that ranks building components from having greatest to least impact reductions. Designers can then focus on decisions that are most impactful and leave others for later stages and work in a more organized and coordinated way.

The building sector is the most important natural resources consumer and the main waste producer, as stated by Soust-Verdaguer et al., (2017). The authors point out the importance of tools and methods to assess overall sustainability of buildings. Their research focuses on the analysis of existing methods of LCA in collaboration with Building Information Management and demonstrate the BIM-LCA exchange (example of this is Tally – a plugin for Autodesk Revit) and the importance of the integration especially in the design phase of the project. The authors see a lack of research that analyzes the BIM-LCA integration and therefore their aim of research was to investigate recent studies about this subject. They concluded that there is still improvement to be made in terms of automating exchanges between LCA and BIM and define this integration in three levels:

- Integration of BIM as a tool for material/element quantification
- Integrating environmental information to BIM
- Development of automated process combining data and software

The authors define that for end users it is crucial to understand the processes involved in the building life cycle, therefore they should have more control over these, while software developers should focus more on the compatibility of different file formats with different tools rather than a development of a plugin. Consequently Eberhardt et al. (2019) emphasizes declining of the service life of the buildings, pointing out cases of 30-40-year-old buildings being demolished for various reasons, this procedure leads to poor exploitation of concretes durability potential. This is especially worrying since cement as the primary intergradient of concrete is responsible for 7-8% of global CO2 emissions according to authors. The study underlines a lack of standard approach for LCA and importance of LCA in quantifying the environmental impact of implementing CE. The author proposes a case study for LCA by using an external software (not compatible with BIM) with focus on allocation of credit due to not clear processes within applying benefits of reuse, recovery, or recycling to specific materials. The authors reflect that by using different allocation method (0:100, 100:0 and 50:50) the results of the LCA would change drastically, since there is no common approach it is not possible to trust the results, especially because the potential future reuse is not a given. In line with the previous findings Santos et al. (2020a) present 3 main LCA directions : (1)use different LCA and LCC tools together with BIM tools; (2)connect the quantity take-off automatically generated by a BIM tool with an external database, thus performing an LCA and LCC analysis outside of a BIM environment; (3)import semantic information into the model to perform a BIM-based LCA and LCC analyses. The 3rd option promotes information integration within the BIM model (especially due to the lack of information in the BIM models in terms of LC, data must be inserted manually). The authors state there is a gap in research on the material and project level in terms of environmental impact and the focus of most studies on the element level only. The study describes the steps of creation of the so called BIMEELCA tool, which is to be used in the environmental and economic assessment of construction projects. The results from the tool might have different Complete Analysis depending mostly on the service life span input and discount rate input (the discount rate does not impact the environmental impact rate but impacts the Net Present Value - NPV). Following on the development of the BIMEELCA Santos et al. (2020b) propose a comparison of the LCA and LCC results using different approaches: BIMEELCA, Tally and ATHENA. The authors use a case study approach with the pre-requisites to conduct a BIM-based LCA/LCC analysis based on a six-step approach. The authors observe a dependency of the LCA/LCC analysis on the location of the project and representativeness of the data input for the materials and elements. In general, after analyzing the results, it's clear that each tool's results vary a lot and it's not easy to perform the analysis due to different scientific models used for developing the tools, so the analysis is limited only to those in common for all 3 tools.

The LCA and LCC tools' inputs can be influenced by various requirements from different assessment approaches, however there is still little to no knowledge about the extent of it. Schweber and Haroglu, (2014) state in their research that little attention has been given to how assessment methods (specifically Building Research Establishment Environmental Assessment Method- BREEAM) act on design and construction processes. Schweber and Haroglu focus on the identification of the effects of BREEAM on project team design decisions, which start at project conception and continue through handover and beyond. The authors analyzed several building projects that they divided into three categories: tight-fit (BREEAM was present at design and building process), punctual-fit (BREEAM present at key moments but not continuously), bolt-on-fit (assessment method had little effect on the design). Schweber and Haroglu claim there is clearly a connection between tight-fit and a high BREEAM score of a project and focus should also be given to contracting methods, communication, and coordination of stakeholders, while prior experience with BREEAM mattered only to a certain level in punctual and bolt-on fit (however, all projects can benefit from prior experience). Overall, the authors highlight the importance of using BREEAM as a design tool as well as an assessment tool to achieve sustainable building projects.

4.3 SUSTAINABILITY ASSESSMENT & BIM TOOLS

Kylili et al. (2016) provide the state-of-the-art sustainability assessment tools and their coupling with LCA methodologies. Among the popular tools, Kylili and her colleagues listed BREEAM, Leadership in Energy and Environmental Design (LEED), ATHENA, Eco Quantum, EcoEffect. Analyzing these systems, they acknowledge the necessity for the introduction of a common framework for implementing LCA studies on assessing the sustainability of building materials, but at the same time in-depth development and understanding of specific country and local data is also needed on the subject. Attempting to tackle the challenges, Kylili presents EcoHestia, a comprehensive environmental impact LCA tool that integrates the most commonly used building elements. The paper then presents a case study where this approach is used in detail. The results from the case study showed the potential of the tool moving towards more sustainable built environment as well as analyzed the most harmful materials used in the industry.

Integration of BIM within sustainability assessment tools is of great importance. Wu and Issa (2015) recognize the strength of PEPG (Project Execution Planning Guidelines), a well formatted, easily understood business processes of BIM implementation and recommended best practices. However, being generic for any building project, Wu and Issa find its use difficult in green building projects. With LEED as the rating system of choice, they propose a new process model, based on PEPG and best practices, to address the unique business process of green BIM projects and verified it on relevant case studies. This process model may be a contribution to solving the concern of Alwan et al. (2015) that although such assessment methods continue to evolve, they have not, as of yet, been integrated into the effective communication, data storage, scheduling and reporting that is now fundamental to the majority of larger, more complex projects being constructed in the developed world and is at the heart of BIM adoption. Further integration of circular practices, assessment and BIM is examined in Jayasinghe and Waldmann's (2020) study. They understand that the estimation of waste, recycling materials and reusable components early on could be vital in waste management. However, conventional buildings are not planned to provide seamless documentation of their materials and the existing tools for the estimation of C&D waste and recycling potential of building materials are not convenient enough for both contractors and recyclers. Therefore, they propose a BIM-based system to allow the circular economy by storing information of the materials and components of buildings and by effectively managing the recycling of materials and reuse of components. This tool can be further be incorporated as a part of a larger early-stage assessment of a project's circularity.

Jalaei et al. (2020) recognize the growing demand for sustainable development and the potential of BIM-based technologies to automate the process of sustainability ratings. The article states that the sustainability analysis is mostly conducted at the end of the design stage, once their components and elements have already been selected, causing reciprocal tasks for the design team to achieve the most sustainable alternative. Therefore, Jalalei focuses on implementing the LEED score potential as early in the design process as possible. With information from the BIM model, google maps and stakeholder answers from a checklist, the created application provides a potential final LEED score at a very early conceptual stage. Like Jalalei (2020) and many others Häkkinen et al. (2015) in their study also stress the importance of decision making at an early stage of design as well as they comment upon the limited research on how to account for embodied carbon as a building is designed. They state that in the beginning of a design process, the opportunities for affecting the impacts of the building – economic, social or environmental – lay open. However, the current standards and tools serve mainly for subsequent assessment of the design. With this research from literature and performed interviews they emphasize the need of alternative design tools that support design for low-carbon buildings within concept and developer design phases. Finally, this paper proposes a new framework outlining each of the project phases, identifying objectives, milestones, and deliverables for gradual low-carbon design approach. The conclusion of the study portrays a positive outlook as they claim that the embodied carbon can be reduced through implementation of carbon footprint assessment during design. Nuñez-Cacho et al. (2018) highlights lack of indicators of CE to measure the application of CE principles in the construction industry. The study presents Industrial Ecology (IE) as one of the pillars the CE concepts were built upon and concept supporting the material and energy flow examination. The authors indicate the relevance of reverse supply chain management in CE as the main factor in achieving close loops of material flow and compatibility of companies with CE. To support the concept the study proposes Product-service system (PSS) where products and services serve as one offer. The authors create an indicator database based on literature review (indicators that had previously been used to measure aspects related to the CE were searched) and sustainable reports of some main construction companies worldwide. The result is a scale of 7 dimensions build of 44 indicators with different weight (importance). The indicators would help to measure the degree of CE implementation on both company and national level. Akanbi et al. (2019) highlights that the government viewpoint on CE has the highest impact on CE implementation according to the construction projects stakeholders. The study is contributing with a REVIT plug-in (D-DAS) that should work as a platform for architects and designers to better asses the design. D-DAS system is built of 4 layers connected to function as one system: Data storage layer proposed to be a NoSQL database due to variety and diversity of data, Semantic layer responsible for data exchange formatting and provisioning to the application layer (XML), Analytics and functional model layer and Application layer. At the functional layer the authors used a BIM-based whole-life performance estimator (BWPE) developed by (Akanbi et al., 2018) At the foundation of these kind of systems lays a semantically rich BIM model, especially in terms of materials composition. If the entire process should be automated the input of required data must be present.

Leising et al. (2018) looked into collaboration in their study and created a new actor collaboration tool for a collaboration project. This collaboration tool went through a thorough process of conceptualization:

- *Vision development* to enhance collaboration by involving stakeholders with relevant knowledge to refine the client's vision and ambition together
- *Actor learning* is essential to embed new collaborative approaches amongst supply chain partners
- *Network dynamics* is facilitating supply chain collaboration by bringing all partners together – from suppliers to designers, demolishers, and waste companies. This calls for trust between supply chain partners, especially among the ones that are normally not involved in the design process.

The theoretical framework based created is then applied on three case projects newly built structure, renovation, and demolition project. Using the tool, the users can navigate through the individual phases of the projects with outlined guidelines and outputs for each stage in order to enhance circularity approaches. The articles conclude that developing circular buildings requires (i) a new process design where a variety of disciplines in the supply chain is integrated upfront, (ii) the co-creation of an ambitious vision, (iii) extension of responsibilities to actors along the entire building supply chain, and (iv) new business and ownership models. Another collaborative framework is explored by Iyer-Raniga (2019). This paper explores the ReSOLVE (Regenerate, Share, Optimize, Loop, Virtualise and Exchange) framework created by Arup and Ellen MacArthur Foundation to support circularity in the built environment. The paper explains 8 key steps for achieving circularity, which are encapsulated in the developed framework. It explains that circularity refers to principles, frameworks or approaches, circular economy refers to the economic and business imperatives required to make circularity approaches a reality. This is because circularity can only work when shared models are successful. Iyer-Raniga further elaborates that not just the building materials themselves and advanced techniques of construction, but also new business models, together with increased digitalization are required so that the socioeconomic system may also support circularity approaches. The framework was applied on 5 different case studies in the paper and the results show that priorities will vary depending on the type of building, site conditions, climate, context, users, type of building, life span, materials available etc. The paper concludes that the ReSOLVE framework enables actors to prioritize practical decisions. Active early stakeholder involvement is one of the main points in a study by Bilal et al. (2019). They see the root cause of waste inefficiency in non-modular building layouts and lack of pro-active collaboration between stakeholders in early design stages. Therefore, Design for dimensional coordination is an important consideration to reduce construction waste through proactive planning at the design stage. The well-coordinated and modular layouts are reported to have improved the waste performance. This study then proposes a convex programming algorithm for Space Layout Planning where spatial units are optimized in the floor layout of a building design based on standard module or material dimensions. This complex algorithm can solve modularity issues by creating a sufficient layout according to the desired measures. Since the authors also stress the necessity of stakeholder engagement early in the project, the algorithm is integrated with BIM-authoring tool, to facilitate designers and asses them early with respect to waste output.

4.4 CONCLUSION OF THE LITERATURE REVIEW

The implementation of CE driven projects seems to be inevitable due to both economic advantages and sustainable agenda, but some gaps and challenges arise from the literature included in the. There is a common agreement among the researchers about the need for introducing standardization for the circular processes, both in terms of exchanging of information (IFC) and development of methodologies for LCA and the collaboration among the actors and the supply chains need to be redefined to meet the requirements of circularity. Given the fact of shortening the life span of buildings, the design processes should be more integrated with environment impact assessment to combine advantages of BIM and CE in the early stages of design where BIM integrated CE tools should be emphasized due to better collaboration options and potential for holistic assessment of the buildings impact and also improve the insufficiency in data management through the entire life cycle. According to the literature the relation to assessment tools as design support tools should shift the attention from short-lived manufactured products to long life and recyclable products and assessment methods should be used as design support tools as well as assessment tools. Essentially the assessment methods should be agreed upon before major decisions have been made which would address another obstacle, namely involvement of all the stakeholders from the initial phase.

The need for BIM enabled MP is emphasized in the literature. The link between the design processes and availability of data within the BIM environment seems to be a crucial part of the sustainable life cycle of the materials and referred to as a good practice approach. The

MP concept is closely related to the idea of buildings as material banks and serves as the foundation for the overall information centered method.

One of the gaps identified by the literature review is strongly related to lack of links or co-occurrence of BIM and CE in academic research and absence of circular projects and consequently deficiency of an actor with an overview over the realization of circularity. Thus, there is a missing link between the project stages that would potentially improve the fulfilment of requirements for separate stages since literature shows the difficulty of choosing only one circular strategy due to complexity of construction solutions and variety of materials and components with different life span and environmental impact.

4.5 SUMMARY OF REVIEWED LITERATURE

STUDY	GENERAL TOPIC	RESULTS/DEFINITIONS
(Aguiar et al., 2019)	Circular design utilizing BIM to reach circular economy	Defines the role of a new actor – the harvester who gathers information, converts BIM model into a circular model adjusted to contain information relevant to material passports and uploads said model together with material passports on a data platform.
(Akbarieh et al., 2020)	BIM based EoL frameworks, DfD, deconstruction, material banks	The study underlines the fact that some components are eligible for deconstruction but not for reuse since they do not pass the reusability assessment tests. The study describes different frameworks for construction waste management with use of BIM. Material classification from the early stage is crucial due to different environment impact of materials.
(Alwan et al., 2015)	Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project	Beyond its immediate aims of experimenting with the links between BIM and environmental rating systems, the significant message from this case study is to reinforce the need to consider and evaluate building performance at the earliest possible stage in a building's design and to allow owners and facilities managers, alongside the design team, the ability to make design decisions and interventions that related to the lifetime of the building
(Basbagill et al., 2013)	Method for applying LCA to early design stages to enable better decision making by providing feedback on the environmental impacts of BIM design choices	Presentation of an automated BIM-enabled decision support framework for early design stage that integrates BIM, LCA, energy simulation, MRR scheduling and sensitivity analysis software
(Bilal et al., 2019)	Design optimization using convex programming: Towards waste-efficient building designs	Algorithm producing an optimized and modular floor layout reducing the construction waste. Enables early stakeholders' engagement in waste reduction.
(Cambier et al., 2020)	Focus on identifying knowledge challenges for supply and demand of design tools for a CE construction practice and the need for support tools	Presentation of available design support tools for circular buildings and the added value they have to the design stages and opportunities to work on new design support tools to improve available tools to aid BIM, LCA and stakeholder cooperation to enhance CE in construction
(Copeland and Bilec, 2020)	Conceptual diagram and framework for implementing circular economy utilizing building as material banks, BIM, radio-frequency identification tags and blockchain	Proposes a framework of building as material banks projects to move on from linear to circular economy by utilizing a BIM system with RFID project information stored on a blockchain database to strengthen the market of secondary materials and improving supply/demand within this market
(Delgado and Oyedele, 2020)	Open standards, CE. Standard data Models for CE	The study recognized the need for standard data models for CE The operational phase of construction projects is emphasized The authors propose entities and enumerated types to describe circular economy principles in a standard data model
(Eberhardt et al., 2019)	LCA of an office building	The study presents agendas and policies towards the CE within the EU and Denmark. The study indicates of shortening of the life span of the buildings, lack of standard approach in terms of LCA, lack of standards in terms of allocation methods for the environmental impact

		and benefits. It states material composition as a significant factor of the buildings embodied environmental impact.
(Eberhardt et al., 2020b)	Systematic review of CE (2013 – 2019)	The study underlines focus of the literature on the ``reuse`` aspects of CE. The result of the review is 16 design strategies for construction projects. Study indicates possibility of a missing link between research and practice. Very limited number of studies describe how the design and construction of a building potentially improved the environmental performance of that building by using life cycle assessment. That brings a risk of choosing wrong strategies.
(Honic et al., 2019a)	Generation of a BIM supported Material Passport that enables an assessment of recycling potential and environmental impacts of building materials and development of data-stakeholder management framework	Demonstration of a concept for semi-automated generation of a BIM-based Material Passport, while suggesting the use of predefined elements. The research proposes a framework for stakeholder management including AEC organization, Regulative Body and Industry and introduces a new role of a MP consultant within the AEC organization.
(Häkkinen et al., 2015)	Assessment of individual project phases and their impact to building's carbon footprint and GHGs.	Stresses the importance of the preparation phase and early design phases in design for environmentally benign buildings. Creation of framework including deliverables, objectives, milestones etc. during various project phases.
(Høibye and Sand, 2018)	Transition towards Circular economy in the Nordic construction sector – Identifying and assessing prominent policies	16 interviewees from Scandinavia suggest 32 policy instruments (information, regulations, economic incentives) to boost transition towards CE in the construction sector.
(Iyer-Raniga, 2019)	Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets	Through case studies of European building projects, the ReSOLVE framework enables practical decisions to be prioritized at the building level.
(Jalaei et al., 2020)	Automating the process of sustainability assessment for proposed buildings by integrating Building Information Model (BIM) and LEED certification system at a conceptual stage	Creation of a Revit application that calculates the potential LEED score at an early project phase through analyzing the model's material database and user questionnaire.
(Jayasinghe and Waldmann, 2020)	Enabling the circular economy by storing information of the materials and components of buildings	Proposed a centralized database as a BIM-based web tool, which is able to store the information from different projects in one location.
(Jrade and Jalaei, 2013)	Development and implementation of a model with database that includes information about sustainable materials linked to a BIM module along with an LCA, certification and cost module at the conceptual stage of a project	Integration of BIM and sustainable design in the early design stage by developing an external database that is linked to BIM tools which includes information about certified components that are recognized by BIM tools. Linking of BIM module with LCA module and certification and cost module is realized through utilizing tools such as Revit, Excel and Athena Impact Estimator. Findings were tested and validated on a model at a design stage.
(Kylili et al., 2016)	Sustainability Tools for the Assessment of Construction Materials and Buildings	EcoHestia performs 'cradle- to- gate' LCA of buildings based on inventory data of construction materials and building elements. It is a decision- making tool, which provides answers in the questions surrounding the improvement of the sustainability level of the building sector with reliable and transparent evidence.

(Leising et al., 2018)	Collaboration within the stakeholders in the supply chain	Creation of an organizational tool for enhanced multidisciplinary collaboration through five phases of construction.
(Munaro et al., 2020)	Systematic review of the CE in the built environment	Study underlines stakeholder's integration, circular business models, government support and new laws as one of the main aspects towards CE implementation. Provides description of research areas, methods, and geographical location. Study claims that resource productivity will become a focus point of the construction industry in the near future.
(Nuñez-Cacho et al., 2018)	Measure indicators of CE within Construction industry companies	Study states a lack of indicators of CE to measure the application of CE principles in the construction industry and proposes a concept of Industrial Ecology as a foundation of CE principles and concept of Product-service system (PSS) as part of reverse supply chain management. If the company did not develop reverse logistics, the production system can't be considered compatible with CE. The authors developed a scale of 7 dimensions built of 44 indicators to support measurability of the CE implementation for both the companies and the government.
(Osobajo et al., 2020)	Systematic review of the CE in the construction industry. (1990 – 2019)	Provides description of research areas, methods, and geographical location of studies. Results: 50% of waste is related to the end life activities(demolition) but only 30% is either reused or recycled. Researchers focus mainly on material reuse (34%) and waste management (30%). The study underlines the urge of more extensive research in the other CE related areas
(Pomponi and Moncaster, 2017)	Basis for identifying and framing fundamental defining dimensions of CE studies in the built environment	Outcome of study is a frame reference proposing six fundamental dimensions for CE research in built environment including the key elements of current initiatives, ideas, and approaches to move towards circular buildings
(Santos et al., 2020a)	LCC, LCA, enriching BIM models with semantic data	Study shows 3 research directions - LCA/LCC tools with BIM, quantity take-off, import semantic information to BIM The study aims to develop BIM-based application for LCC/LCA automatic analysis and to demonstrate how to identify elements and materials with high environmental impact automatically at the very beginning of project There is a gap in research on the material and project level in term of environmental impact. Most of the studies focus on the element level only. The developed tool (BIMEELCA) allows to add information to the model itself.
(Santos et al., 2020b)	LCC, LCA, enriching BIM models with semantic data	Currently, the use of BIM to extract the bill of materials and connect it with external databases is the most used approach Comparison of the LCA and LCC results using different approaches: BIMEELCA (tool developed by the authors for BIM-based LCA and LCC analyses), Tally (Revit add-in with connection to the external database), ATHENA (uses bill of quantities, not integrated with BIM) As a result, the authors state that the LCA and LCC analysis depend greatly on representativeness of the source and the selection of tool depends on the location of the project and purpose of the analysis outcome. ``It was observed that the integration of LCA and LCC analyses with BIM is greatly influenced by the databases' flexibility``

		In general, after analyzing the results it is clear that the each tools results vary a lot and it is not easy to perform the analysis due to different scientific models used for developing the tools so the analysis are limited only to those in common for all three tools.
(Schweber and Haroglu, 2014)	Examination of the effect of BREEAM assessment process on design and construction processes on case studies by developing an analytic framework, while also including methods such as LEED and GreenStar.	The research identifies relevant elements to achieve a high BREEAM score and provides a connection between assessment and construction processes. An important factor was also identified as the relation between the assessor involvement and project-level characteristics as the assessor the assessor does not determine the fit of the assessment to the project. One feature that impacted the effects of the assessment on processes was the commitment of the stakeholders and the inter-organizational collaboration. Another finding of the research is one of using BREEAM as not only an assessment tool but also a design tool to achieve desired score while highlighting the assessor (and their involvement) as an internal part of the processes to work towards shared commitment and overall project sustainability
(Soust-Verdaguer et al., 2017)	Review of BIM-based LCA studies and analysis of their integration and how BIM can aid to simplify data input and optimize data output when using LCA to estimate impacts	Research shows and analyses the existing methods of BIM-LCA integration and demonstrates limitations of the BIM-LCA exchange. It defines the BIM-LCA integration in three different levels, where the third involves the development of an automated process using a combination of data and software. The paper also references the appropriate level of development (LOD) to verify environmental impacts during early design stage. From the users' perspective, research highlights recommendations and challenges for the end users and developers to improve tool integration.
(Van den Berg et al., 2019)	Circularity challenges and solutions in design projects: An action research approach	This research follows a school renovation project that aims to be done in circular fashion. It portrays the design challenges and suggests solutions to overcome them. It provides a 'real-project' insight and explores new opportunities to better understand and deal with circularity challenges in design.
(van den Brink et al., 2017)	Business models for stakeholders of construction projects in terms of CE	The study underlines the lack of knowledge of how the construction processes will look like if the project implements the CE. The study proposes a new stakeholder within construction projects – Service provider The study offers 5 service business models for the SP to choose from, depending on variables and services provided by the SP The study presents the roadmap for advanced circular services. but it is more likely that the short term to intermediate circular revises will appear.
(Velasquez et al., 2020)	Analysis of the role of Information and Communications Technology (ICT) enabling Circular Economy based on Product Life Cycle Management (PLM)	Research mentions ways ICT could be beneficial towards CE transition in Beginning of Life, Middle of Life and End of Life of building materials and defines opportunities and challenges of linking CE and PLM through ICT
(Wu and Issa, 2015)	BIM execution planning in green building projects: LEED as a use case	Study propposes a new process model, based on PEPG and best practices, to address the unique business process of green BIM projects and verified it on relevant case studies

Table 3 Summary of reviewed literature

CHAPTER:

5. PROBLEM FORMULATION

This chapter will introduce the problem formulation of this research and its subsequent questions related to it.

The initial research performed in the literature review identified gaps in the implementation of circular economy into construction projects and pointed out the lack of BIM application to aid the circularity process and actor involvement and collaboration especially throughout the design phase of projects and continuing into the entire buildings' lifecycle. The literature review research also indicates many varying circular approaches within the AEC industry which can lead to difficulties with circular economy implementation in the project and with missing demand and requirements often resulting in little to no motivation towards circularity as well as a lack of push towards circular economy in construction project. Therefore, the aim of this study is to identify the standardization needed for circular economy implementation and a framework of circular construction processes. The problem formulation is as follows:

''How can BIM support early design processes to enhance Circular Economy approaches within building projects?''

It is presumed that implementing such a large concept as circularity into projects will alter the existing construction project processes as well as affect the handover between the different phases of the project and stakeholder collaboration. Moreover, implementing circular economy comes with additional data being applied to construction components and an issue of handling said data can arise.

Therefore, the below secondary questions are also analyzed and answered in this report:

How does integrating CE into early design affect existing construction project processes?

How can data needed for circular project implementation be sufficiently handled in the BIM environment?

How do we ensure a smooth transition between circular project phases and stakeholder collaboration?

CHAPTER:

6. ANALYSIS

This chapter explains the interviews performed and the reasoning behind the choice of interviewees and their expertise. Furthermore, it describes the analysis of the collected data to set a foundation for the solution chapter.

6.1 INTERVIEWS

To gain a different perspective on the existing processes, problems, and gaps with circularity in connection to BIM and stakeholder collaboration within companies, interviews are chosen as a form of secondary data collection, following the literature review. The interview is set up as a semi structured interview and for best data collection to fit the aim of the research a fact finder/exploratory interview type is selected. The question template for the interviews stems from the topics of the reviewed literature to fill the gaps and to gain knowledge of company practices in the industry. The interviews are performed with industry professionals including architects, engineers, sustainability consultants, BIM professionals, and PhD students currently handling topics related to circular economy. Those interviewees are selected according to their expertise and type of position they work in to gain knowledge from the following three subjects:

Sustainability & CE in the industry: To gain knowledge on how CE and sustainable design is viewed, treated, and applied in the AEC industry, professionals working in related areas were selected. Therefore, sustainability consultants & managers currently working at Danish construction companies are the choice to cover this subject.

CE in the industry in perspective of the academia: The literature review demonstrated a great effort in research of CE in the AEC industry, but also has shown the lack of implementation on project, company, or governmental levels. To gain more knowledge on this issue, industrial PhD students are selected, because they best represent bridging the academia and implementation in reality.

BIM-enhanced CE in the industry: To gain knowledge on how BIM is currently supporting, if at all, the transition toward CE in the AEC industry, professionals working with BIM are selected. Therefore, BIM experts, architects, and engineers working at Danish construction companies are established to cover this subject.

Three interviews per each subject, resulting in total of nine interviews with industry professionals are conducted and transcribed. The Table 4 below shows all the interview participants and their position.

Position	Company Type
Sustainability Consultant	Construction Company
Architect/Teacher & Research Assistant (area of CE)	Academia
Sustainability Consultant	Consulting Engineering Company
Industrial PhD Student within CE	Academia
Sustainability Manager (DGNB specialist)	Construction Company
Architect	Architectural Company
Civil Engineer/Industrial PhD Student within CE	Road Directory
BIM & ICT consultant	Construction Company
Structural Engineer	Consulting Engineering Company

Table 4 Nine industry professional interviewees

6.2 INTERVIEW ANALYSIS

The aim of the interviews is to establish a foundation for professional perception of the research area. The next step requires analyzing the data to uncover the potential of the material therefore, the following pages are focused on organizing the facts and opinions of the interviewees into logical and easy to comprehend set of information.

6.2.1 Familiarization

There is a slight difference in understanding and defining the concept of circular economy, however, most see the concept from both the sustainability view and the economical view of the project and "see a great potential for the implementation of circular economy" for future projects to limit resource use.

Most interviewed representatives of companies see the relevance in the implementation of circular economy into their project as they see the investors and building owners being more interested in the topic in the recent years. As one interviewee states: "they (company) are interested in circular economy because they can see the investors like that, they are cutting edge on sustainability.", while another one mentions following: "We find that the building owners, such as municipalities and big investors are starting to mention CE principles in their calls for tenders."

Some companies do have internally established requirements within CE workflows: "…we do have restrictions that we have to follow, and we also have very clear ideas that we want to be certified for most of what we do…", "…we publish internally the new guidelines and how we work on circularity and the DGNB lifecycle assessments."

However, most of the interviewed companies do not have established CE workflows or lack CE implementation altogether. The lack of demand and initiative in circular economy implementation was mentioned by some interviewees, as one participant states, "it needs to come from a governmental side" and another adds "I have not worked with CE on projects, because of lack of demand". However, the issue that seems to play a very big role in CE implementation is standardization. The actors are "…provoked by the fact they should do things in a standardized way" and the lack of standardization was mentioned as the "…lack of explicit requirements", the CE concept being viewed in a different way globally and the lack of standardization in LCA tools. All these issues seem to stem from a statement that "there is not yet a standardized way of defining how to do circular economy".

Three out of nine interviewees clearly state that there is a lack of CE implementation in projects, due to the norms and standards: "the pressure is made in legislation and ultimately, that is what we need." One interviewee sums up the goal for successful CE implementation – "we need to kind of develop that approach on how to actually define the flow of existing building materials from tearing it down to the implementation in new building projects or renovation projects."

There is also a push from the companies to implement circular economy earlier in the project to "say how that can also really save costs and be cost efficient – also later in the process"

Most interviewees agree to use life cycle analysis as a circular economy driver as a base for decisions – "…because if you do it earlier on, it is, of course, a lot easier to make changes" as many times they see that "…often the LCA results are not used" and "…LCA was not used for decision making." However, often, if the initiative does not come from a client, the company would not perform a life cycle analysis on their project – "If the client has an ambition for the most sustainable solution, we make an LCA analysis.", "…it would normally not be for the sake of the certification, but more of an answer to the client's expectations for sustainable design choices."

The perception of the BIM concept seems to be the same among the interview participants with the common understanding of BIM as a "way to digitally gather information" and "a way to save and monitor things that have been done…to facilitate interactions". One company representative sees that "BIM can be a mapping tool if you think of the building as a material bank", "material passports could in one way or the other also make the road easier in regard to replacing building components and materials and storing them in the right way and put demands upon the more sustainable materials into the buildings" and some see the future of BIM being could-based.

BIM is also viewed as a supporting tool to digitalize the process of circularity, "…BIM models are a very relevant data source for circular economy… I think it is very relevant to look at the BIM models and I don't actually see how we can make a more efficient facility management…" and the companies see a potential in using BIM in aid to circular economy implementation: "…I really hope that as BIM progresses, it is just a case of plugging in this information that is readable or useful…"

The interview participants are also asked about the stakeholder collaboration within their companies and if they as individuals view the project roles changing with the implementation of circular economy and how.

Some company representatives agree that stakeholder collaboration is not as fluent as it could be: "I would actually say that one of the contradictory things within the building sector is that the different parts of the value chain do not necessarily understand each other very well" and suggest to "…be very considerate about the ways that we work as different professionals in the early phases and how to make that happen in a computer aided process". Two interviewees bring up the issue of stakeholder involvement: "…entrepreneurs as such, they are a little reluctant to work with such (CE) issues until they actually observe few requirements for it.", "I think most engineers would like to get involved earlier because of the dialog between architect and engineer could be relevant to have earlier in the project…"

Three company representatives agree that the current roles are generally sufficient to support CE projects: "I do think that the core competencies are good", "…I think as long as the data is available, then it facilitates everything", "I think from a more generic point of view I think so (current roles are sufficient to fully support CE), while some specifically talk about the BIM manager role: "I do not see the BIM manager have a different role.", "…I do not see what the BIM manager role should otherwise be."

One participant defines that the roles are in constant change, while others see the potential in evolving the roles of advisors, specifically for improved communication with the client and the architect having more views on the project than just the esthetic, while one suggesting "…that can also be a new role…to first drive the process of the building from the construction to its use, but also drive the rest and facilitate the transition at the end of life of one thing and the construction of a new thing.

Some interviewees agree on the role and competence change for the BIM manager role:"…it would be a job that goes from being very technical to you have to also think about the environment, the economy", "…one of the competences that they would probably benefit from is knowledge about sustainable materials and how to search for sustainability and sustainable materials and components", "I would bet that I (BIM consultant) would get more included in the project regarding the handover and have a closer dialog with the client."

However, there are also participants that see the issue being more in the mindset of actors rather than new roles or competencies: "…I think it's more about changing the mindset of the people rather than hiring new people or getting new tools." "…it takes a long time to actually change that mindset in the construction industry where you are used to doing things in your own way…I hope that it will come with the younger generations that will put demands on older generations regarding standardized thinking to raise the quality."

Another aspect mentioned that could be affected by the implementation of circular economy in projects is the overall workflow in the company – "…a major issue today is that there is a discrepancy between what we can do with the materials and what we do with the structures", "…my hope is that I can help the company create a smarter way of doing the project plan…so it would be easier to use circular solutions".

6.2.2 Themes and Codes

Following the thematic analysis approach, the crucial information from transcribed interviews is categorized ang grouped into themes using colors for better navigation through the data. This move allows for better overview of the gathered data and helps to determine emerging patterns, potentially supporting the attempt of addressing of the problem formulation. The initial coding and themes are presented in Figure 12, the colors assigned to them are upheld throughout the study. The main circle contains the 10 themes. Each of the themes are supplemented with specific codes (the theme General Information is kept alone intentionally due to generic nature of data).

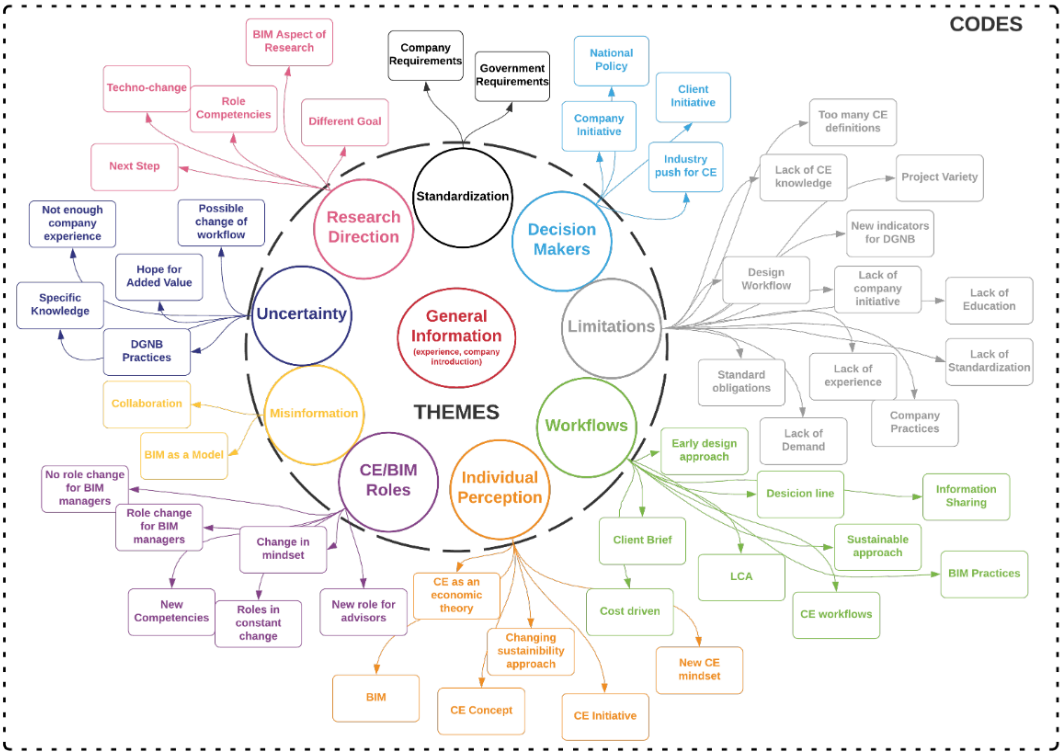


Figure 12 Codes and Themes (own illustration)

After the first round of analysis some of the codes assigned before are grouped together (Figure 13) to get better perspective on the value of the information and due to underrepresentation of the data allocated before.

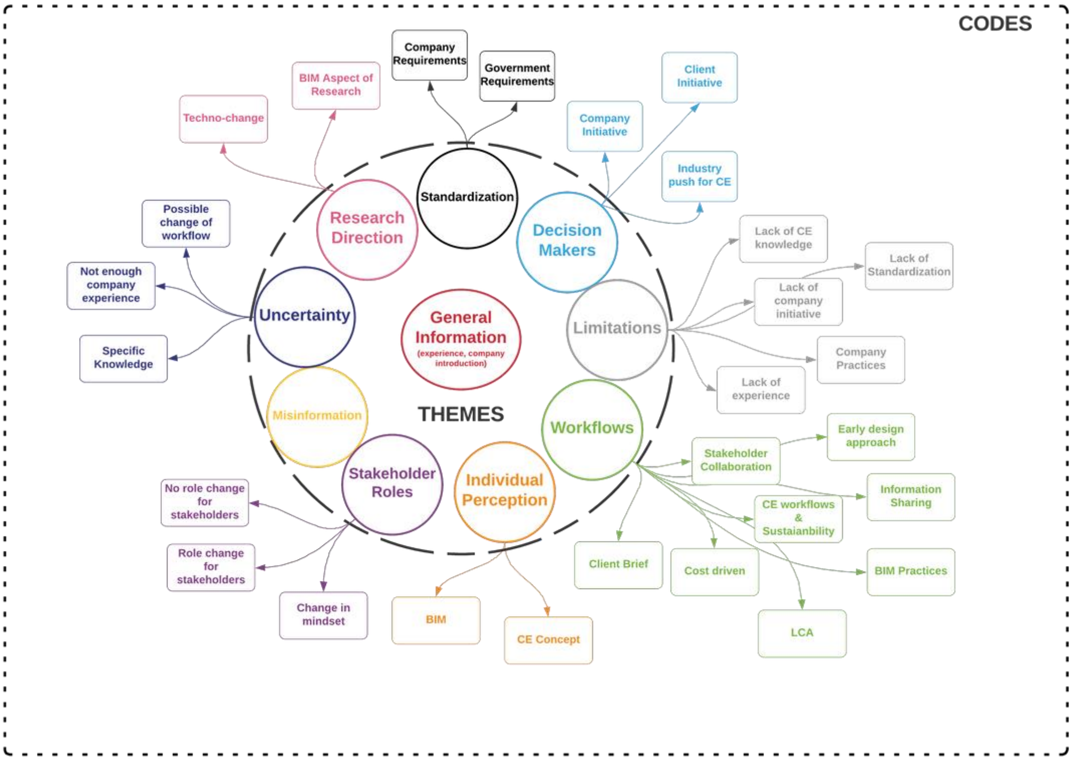


Figure 13 Reduced codes (own illustration)

Under the theme **Individual Perception**, the codes are reduced to only: BIM and CE concept, to centralize importance for the study insights. The theme **CE/BIM Roles** is renamed to **Stakeholders Roles** and the codes are centralized to get overview of the possibility of roles and competencies evolution and stakeholders' involvement in circular processes. The same procedure is applied to the other codes and the result can be observed in Figure 13

Closer investigation of the full text, codes and themes leads to developing clusters of codes under 5 main pillars: **Standardization, CE Knowledge, Early Design, Stakeholder Collaboration and BIM Expertise.** These pillars are understood as the foundation for the main areas of the circular driven projects as derived from the professional perspective of the actors involved in the processes of the AEC industry. The cluster can be observed in Figure 14.

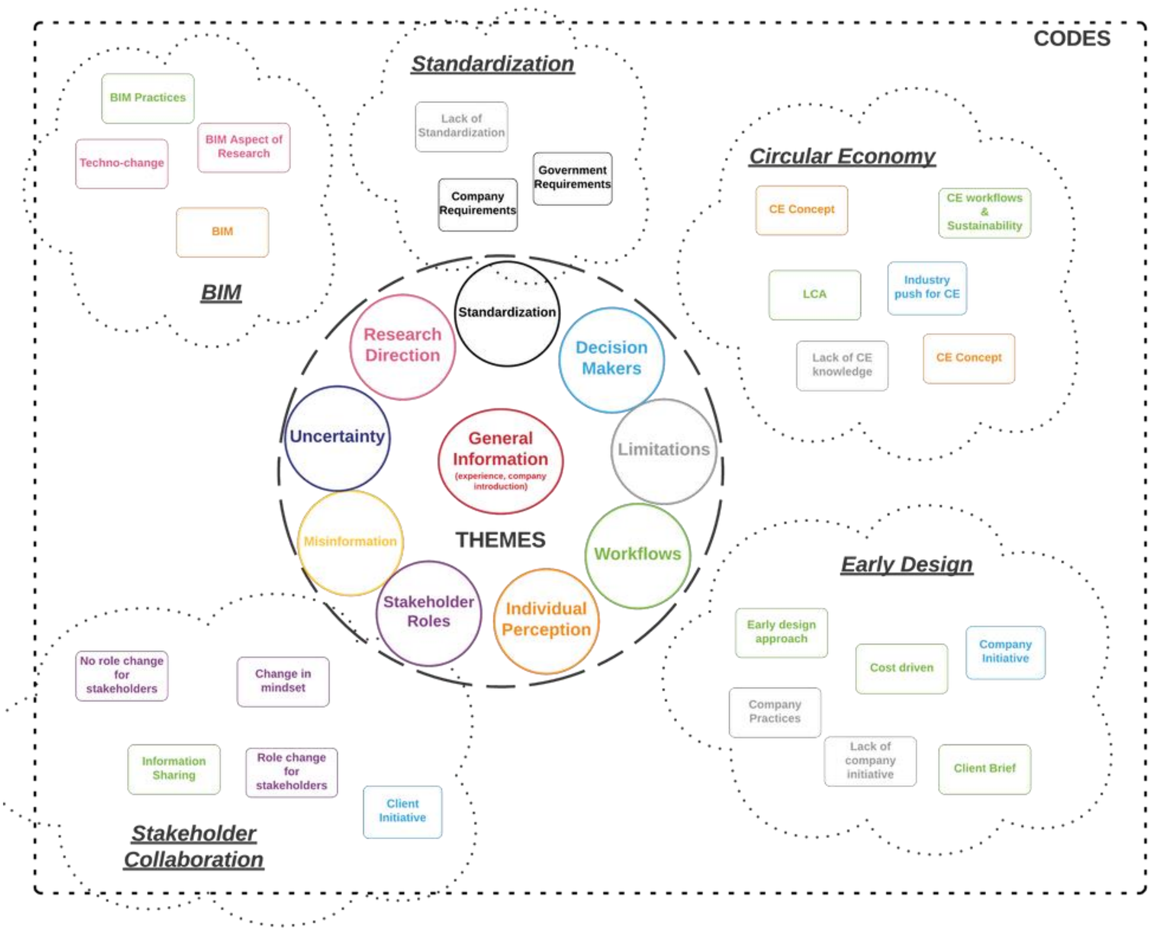


Figure 14 Cluster of codes (own illustration)

Standardization, as one of the main drivers towards the circularity of buildings both on national and international level, serves the purpose of bridging the gap of high variety of projects in the built environment. Standard approach is very important also on the company level, as emphasized by the interviewees, but must be supported by demand from the governmental units.

CE Knowledge in this context is a wide cluster of workflows, limitations, and individual definitions of circularity. The limitations aspect is one of the leading parts of the implementation of circular projects and requires a great deal of industry push towards putting it into practice. The promotion of sustainable ratings creates a pull from the clients both private and public towards the CE, as a result there is an increased interest of companies to fulfill the new conditions.

Early Design phase is acknowledged as the crucial moment for LCA by both the interviewees and the academic literature. The LCA is accepted as an important part of circular planning of buildings. The approach for early design depends on the internal workflows of the company and is determined by the client's requirements.

Stakeholder Collaboration emerges as a mainstay for the success of the circularity in the AEC industry due to the undeniable importance of information sharing. This aspect will become even more central with advancement of circular projects and therefore requirements arise towards new competencies and knowledge for the actors.

BIM Expertise is portrayed as creditable source of information about the building both during the construction phases and during maintenance. In terms of circularity and reuse of building materials and components it serves an important role according to the data gathered during interviews. The technological advancement is seen as a great opportunity for the improvement of circular projects and creates possible change for BIM consultants in CE enhanced processes.

The pillars and the full text are examined once again to achieve coherence with individual responses of the interviewees. Some questions cannot be answered to their full extent due to lack of experience within a company or the lack of specific knowledge within an area. Some uncertainty to answer the interview questions raise from the PhD interviewee group not having enough experience with the company yet, resulting in answers such as "I don't know enough about the company to answer the question" and "…I'm not directly involved in their daily projects". Nonetheless a large share of the responses falls into the 5 pillars, some of them can be viewed in Figure 15 and on the following pages. The main purpose of this procedure is to establish a common ground between the interviews and the proposed pillars and to enhance the work on the possible clarification of the issues involved in the implementation of the CE driven projects as portrayed by the professionals.

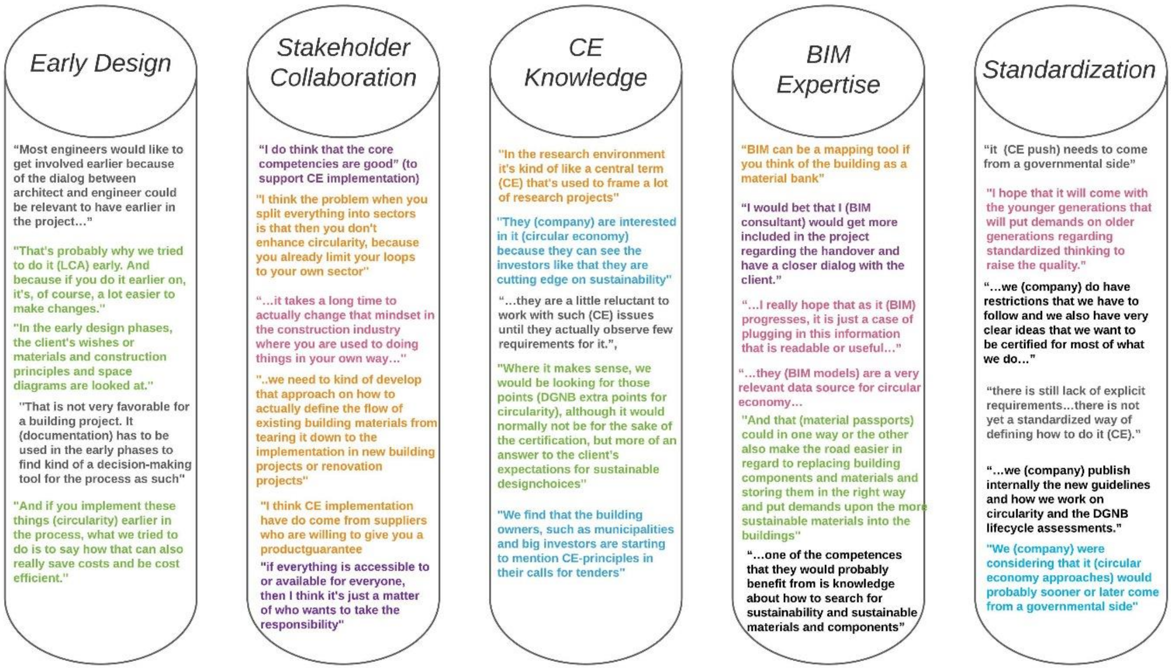


Figure 15 The 5 pillars with supporting quotes. (own illustration)

6.3 SOLUTION FOUNDATION

Through the codes, themes, clusters of codes and in-depth analysis of the full text the 5 pillars emerge. The concentration of the codes allows to grasp the full meaning of the transcribed text but does not bring any unanticipated facts. In order to discover the full potential of the interviews the codes are clustered together, and the data is examined again. The clusters are turned into pillars with the quotes supporting each of them. The concept of the pillars is to set up a foundation for seizing the crucial aspects of the workflow towards circular projects and an attempt to uncover possibilities to support their realization on the operational level of the AEC companies

Together with the gaps uncovered through the literature review such as lack of standardization, collaboration inefficiencies and missing overview of circular processes within construction projects, the pillars form a backbone of the proposal for addressing these issues. To lay a good foundation for the proposed solution, the existing process map is prepared based on RIBA plan of work template for 2020 (RIBA, 2020) and can be seen in Figure 17. This process map is a simplified overview of the general practices in terms of planning and design phases of construction projects. The structure will help to introduce an upgraded map with CE enhanced approach to visualize the best practices for the implementation of BIM supported circularity into the early design and planning phases. The workplan prepared by RIBA claims to be procurement neutral allowing for adjustments by each stage to accommodate necessary requirements. Nevertheless, the crucial impact is allocated to Technical Design stage (RIBA, 2020) and, by this, aligning itself with the top of the curve (Figure 16) for the Preferred Design Process showed by (Sacks et al., 2018) and related to BIM involvement in AEC industry.

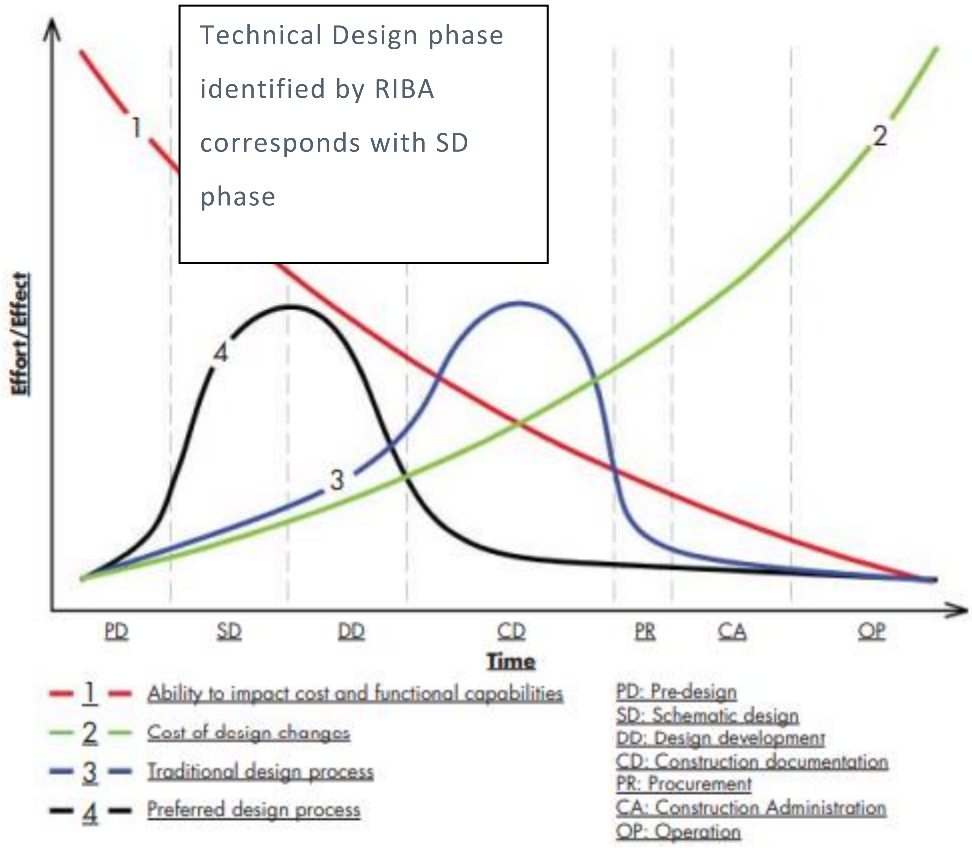
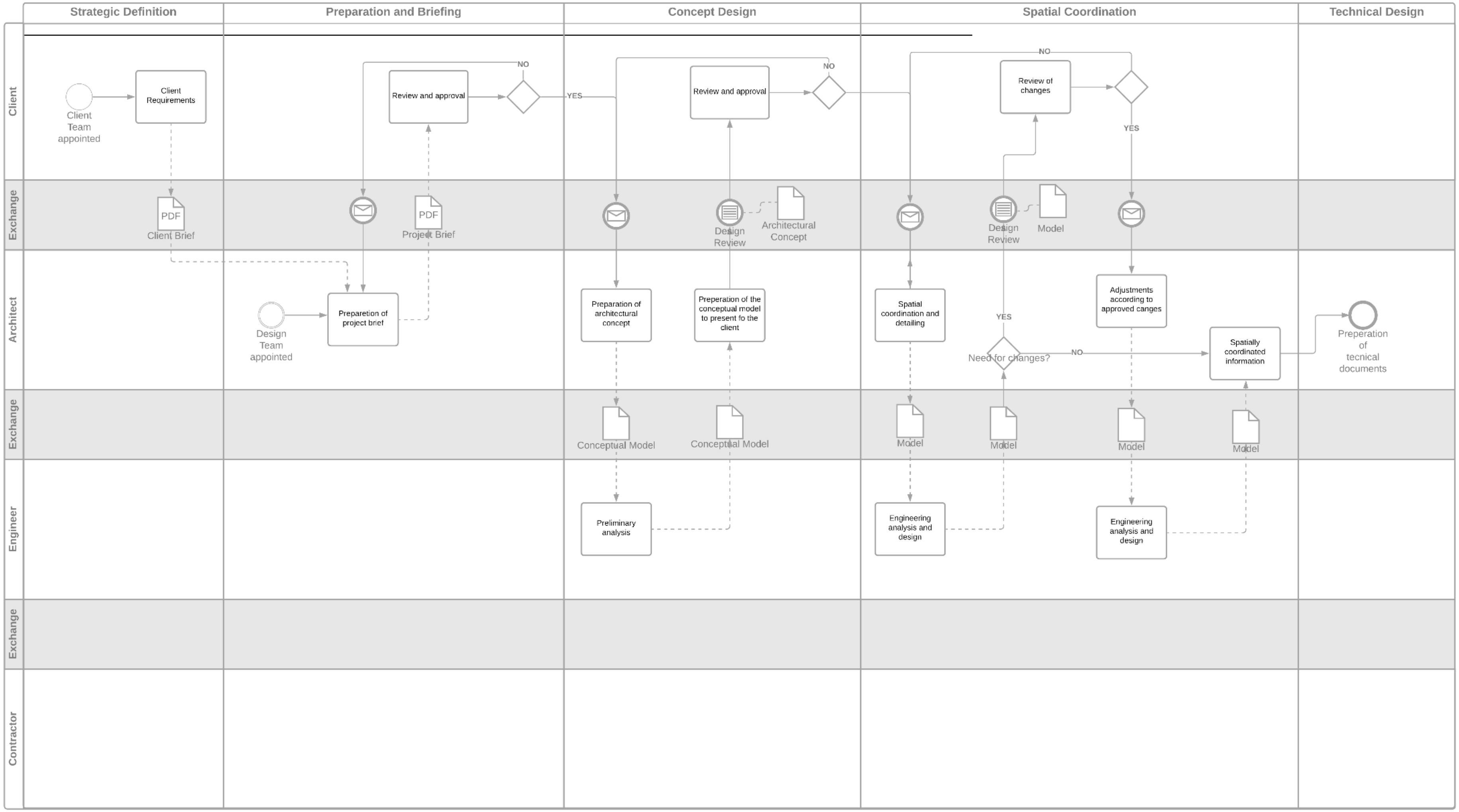


Figure 16 Preferred Design Process (Sacks et al., 2018)

According to (Sacks et al., 2018) this so called ``front loading`` of projects allows for better cost efficiency and increased impact on changes in design, and aligned with procurements highest impact serves as the cut off line for the process map of existing workflow for design processes as seen in Figure 17.



	Client Brief	Project Brief	Architectural Concept	Spatial Coordination	Technical Design
Elements of stage outcomes	- Client requirements - Bussiness case (strategic decisions) - Extend of stakeholders - Available budget - Spatial requirements -	- Project outcomes - Quality aspirations - Sustainability considerations - Procurement strategy - Feasibility study (spatial requirements) - Information requirements - Responsibilities	- Site information - Achieved spatial requirements - Eng-arch congruence - Cost plan (outline specifications) - Route to BR compliance - Stage report (respnsibility matrix, design and project programme)	- Validation of architectural concept (spatially coordinated) - Engineering analysis / studies - Cost plan aligned with the budget - Project strategies (design programme) - BR review - Planning application - Quality Aspirations met	

Figure 17 Existing processes map based on RIBA, (2020)

One of the key aspects of the BIM enhanced circular projects uncovered by the literature and interviews is set to be the Material Banks and Material Passport. The MBs and MP aim to be a resource of data throughout the entire life cycle of a building (Honic et al., 2019a) starting with the optimization of the design in early processes by shifting the focus to the data centered solutions. For better CE implementation the requirements towards circularity of information must be clearly stated in the Clients Brief and then reflected into the Projects Brief (RIBA, 2020), thus allowing for the MB to uncover its potential in promoting the link from BIM to MP and MB and finally to various stakeholders of the project.

The concept of MP comes with the need of producing and storing large amounts of data. There are different options to utilize this process but the most future proof and collaboration oriented is the web-based storage solution (Honic et al., 2019a). The combination of web-based database and open BIM described by Dankers et al., (2014) allows for keeping the data outside of the model, thus not effecting its performance. The information provided by the MP must be standardized and accessible from the early design stages in order to achieve compatibility with the model, also the modeling itself inside the BIM tool must be done in a standard way or at least following the general modeling guide, as presented by Honic et al., (2019). This approach lets the information on the specific objects of the model to be able to be linked to an external database to serve as a foundation for the MP.

The BIM based LCA is recognized as another important aspect of CE implementation, especially that the data input for the LCA is aligned with the MP and could be integrated into the MP. The material passport requires additional indicators for recycling but nonetheless it would profit from improved data exchange between BIM and LCA – this could be done by standardizing the material properties in both. The existing BIM based LCA procedures follow the indicators from only the LCA tool and cannot be changed in BIM. This move would also be a step towards automation of the of the process, thus reducing the manual input of data (Honic et al., 2019a).

The process map of CE enhanced processes and information exchange is be presented in the next chapter together with data requirements for the MP and possible scenarios for storing and quarrying the data in web-based BIM environment and position of LCA in that process.

CHAPTER:

7. PROPOSED SOLUTION

This chapter introduces the solution for the project based on the five pillars derived in the previous chapters. The solution consists of a newly developed workflow proposed to be implemented for construction projects. The new workflow is multi-layered by professions and very extensive with many topics that need to be addressed, however, due to the limited time of this project, four areas that are further explored are highlighted within the process map.

As an outcome solution to the problem, a process map of a new workflow based on the 5 pillars is developed in this chapter. To cover the gaps identified earlier the map is divided into the focus areas and crucial aspects of CE enhanced workflow are emphasized and described. The proposed processes are facilitated by a gateway CE assessment (see chapter 9.5) of the separate phases of the projects in an attempt to standardize the procedures and highlight the importance of early design stages, BIM enhanced MP and MB for the circularity of buildings.

7.1 NEW WORKFLOW SUPPORTED BY PILLARS

The pillars in Figure 18 are the visual representation of the critical points of CE implementation in the AEC industry. The 3 bottom pillars: Standardization, BIM Expertise and Stakeholder Collaboration form a foundation to support the Early Design and consequently the Circular Economy Knowledge. The foundation provides the necessary changes to the new workflow for making it suitable for CE driven projects:

- Standardization – provides official guidelines for the stakeholders to follow on national and global level. These standards create a base for common understanding of practices in terms of design, analysis, ontologies, and digital means.
- BIM Expertise – provides the perks of digitalization era and secures the data management and ease of information availability for the stakeholders. The MP and MB together with BIM data form an ultimate tool for LCA, Circularity analysis and improve information flow through all the stages of the project and stands in the middle of the proposed map.
- Stakeholder Collaboration – provides clarity of responsibilities and tasks, enabled by standardization and BIM promotes the information exchange practices of the new workflow. Thus, regulate free access to data at any given point of the project.

The Early Design pillar is the representation of the stages covered by the process map. As stated in chapters 4.4 and 6.3 the early design is a key moment for implementation of the circularity, the processes initiated at this stage will support the information storage and exchange between the stakeholders and provide an overview of potential reuse possibilities, environmental impact, and life cycles of building components.

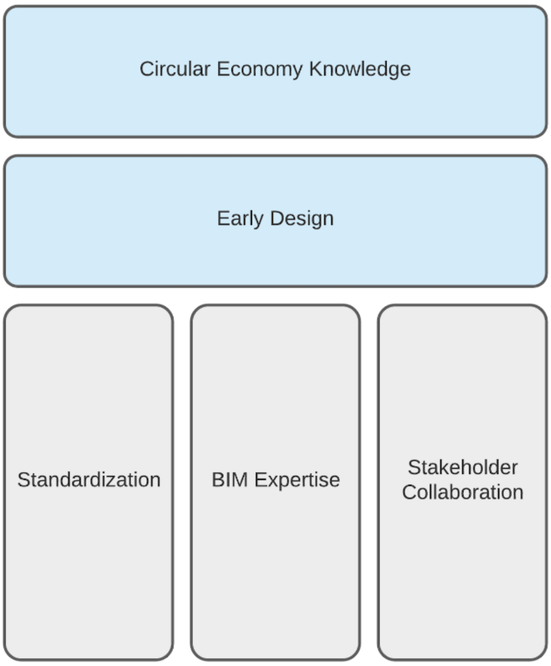


Figure 18 Pillar supporting formation (own illustration)

The Circular Economy pillar is an inevitable outcome of the proposed workflow, but as stated in chapter 2.4 the fragmentation of the AEC industry makes it difficult to proceed towards this common goal of circularity and chapter 4 underlines the lack of research of BIM and CE as coexisting concepts working together to promote the new approach regarding design options and data storage in a standardized manner. Therefore, the map in Figure 19 is based on principles combining all the mentioned pillars to support the move in the direction of BIM enhanced circular projects with data available to all the stakeholders but also putting pressure on them in terms of uploading the information and updating it constantly through the entire life cycle of the building and possibly the next life cycle of the reusable components.

The process map in Figure 19 depicts the proposed outline for project stakeholders to navigate through, ensuring standardized workflow for projects in early-design stages to move closer towards circular projects. With circular approaches and BIM techniques as an outset, all four early-design phases describe the responsibilities of the involved actors, the tasks to be carried out in individual phases and the standards to facilitate the processes.

The workflow in Figure 19 highlights four separate areas of interest (1) MBs & MPs, (2) BIM-based LCA, (3) Input of MB data, and (4) CE phase gateway assessment. These four areas are further elaborated on and described to cover the technical aspects of the processes to some extent and provide the purpose of them.

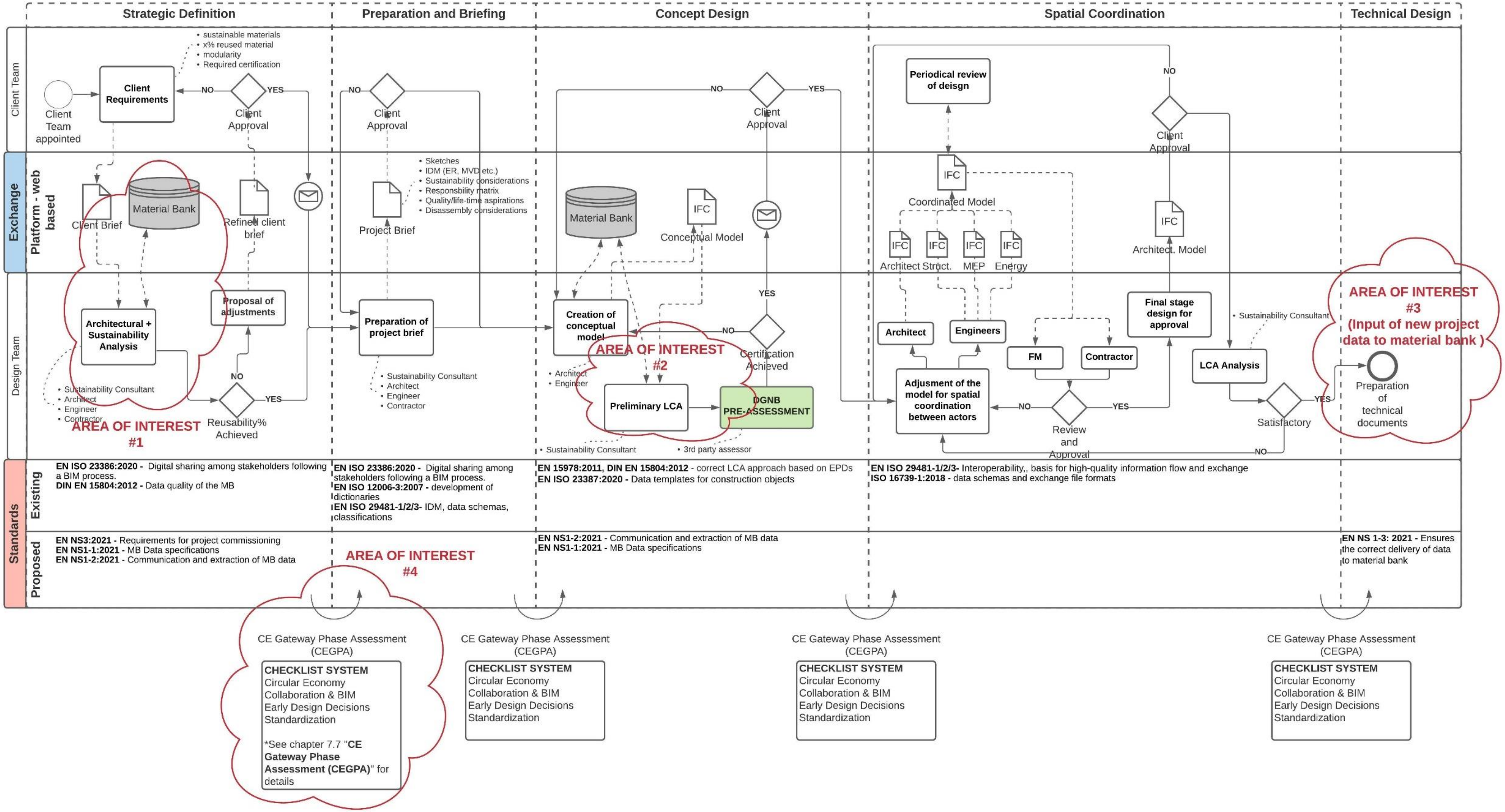


Figure 19 The proposed workflow in form of a process map (own illustration)

7.2 USE OF STANDARDS

The use of standards as mean of facilitation and support of the process is a very important addition for the workflow's purpose. As can be seen in Figure 19, the standards are only shown in each of the phases they are to be introduced, but they are to be referred to in any subsequent points of the project if relevant. For the purpose of this research, a number of existing standards (Table 5) are picked to set an example of how they would appear in the process, it is necessary to note that the number of standards and codes used if implemented must be extended.

Reference*:	Title:	Description:
EN ISO 23386:2020	Building information modelling and other digital processes used in construction - Methodology to describe, author and maintain properties in interconnected data dictionaries	Establishes the rules for defining properties used in construction and a methodology for authoring and maintaining them, for a confident and seamless digital share among stakeholders following a BIM process.
EN ISO 23387:2020	Building information modelling - Data templates for construction objects used in the life cycle of built assets - Concepts and principles	Principles and structure for data templates for construction objects to support digital processes using a standard data structure to exchange information.
EN ISO 12006-3:2007	Building construction — Organization of information about construction works — Part 3: Framework for object-oriented information	Specifies a language-independent information model which can be used for the development of dictionaries used to store or provide information about construction works.
DIN EN 15804:2012	Building Sustainability – Environmental Product Declarations – Basic Rules for the Product Category of Building Products	Supports the application of environmental product declarations for the assessment of environmental properties and health and comfort aspects of buildings
EN 15978:2011	Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method	Describes the calculation method, based on Life Cycle Assessment (LCA) and other quantified environmental information, to assess the environmental performance of a building, and gives the means for the reporting and communication of the outcome of the assessment

ISO 16739-1:2018	Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries — Part 1: Data schema	Specifies data schema and exchange file format structure. Language definition of data schemas is further referenced in ISO 10303.
ISO 29481-1:2010 **ISO 29481-2:2012** **ISO 29481-3 (UD)**	Building information models — Information delivery manual	Describes the methodology for interaction and coordination framework for actors, maps the responsibilities of a process context for information flow and ensures interoperability between software applications used.
*The table is extended by content of all referred documents within the specified standards		

Table 5 Existing standards referred to in the process map

The new workflow has a variety of processes and responsibilities for projects that are not yet described in any standards, therefore, list of proposed standards that need to be developed to aid the process is suggested (Table 6).

Reference:	Title:	Description:
EN NS1-1:2021	Material Banks – Quality & structure of data	Description of MB database structure and specifications for material bank data
EN NS1-2:2021	Material Banks – Communication & Extraction of data – Schemas for information exchange	Description of MB database structure and framework for communication and retrieval of data
EN NS1-3:2021	Material Banks – Input of new project data at awarding of building permit	Description of correct input of data from a new project to the MB. It should cover the level of detail, file formatting, and information structure
EN NS3:2021	Circular Economy – Requirements for Project Commissioning	List of points that need to be addressed by client team within Strategic Definition phase. It also includes description of the points and how to fulfill them.

Table 6 Proposed new standards referred to in the process map

Standardized workflow supported by the correct documents is a necessary move for projects to become more circular (Van den Berg et al., 2019), therefore specification of the relevant documents at time they need to be referred to is crucial.

7.3 MATERIAL PASSPORTS – CONTENT INFORMATION

In the context of the process map in Figure 19, this chapter portrays the area of interest #1 and all the subsequent points in the workflow that mention material passports.

Gathering the data needed for the MP is a difficult process mostly due to the inconsistency of naming of the specific elements and indicators and the units provided with the data in different databases. Since the information needed is closely related to the LCA the general data accumulation for both consists of 3 main sources(Honic et al., 2019b):

- LCA-database (e.g. GaBi) provides indicators for specific materials.
- Construction elements journal provides composition of elements according to standards.
- EPD (Environmental Product Declarations) as a part of data provided by the manufacturers.

In order to avoid inconsistency, the best practice seems to be compiling the data from one source only but this move leads to oversimplifying the results and limits the overall number of indicators, thus hinders the holistic approach so much needed for the implementation of CE principle promoted by the European Commission and BAMB(Heinrich and Lang, 2019).

No matter the database used for querying the data there are some CE indicators needed to be attached to the materials, elements and buildings as whole following the hierarchy for MP presented by (Heinrich and Lang, 2019):Material, Component, Product, System, Building. Different levels information has different roles at different stages of the project and build upon each other in order to add valuable data for reusability by e.g., describing the ingredients in a specific material, types of materials in a component, their connection to each other, and location within the building. The overall information requirements towards configuration of MP can be divided into 4 categories: Physical, Chemical, Biological, Process (Heinrich and Lang, 2019). These properties apply to all types of materials but might have different importance for the specific analysis, assessment tools and stakeholders acquiring the data. In terms of CE, the indicators with the most importance would be covering the knowledge of e.g., expected lifetime, ease of recycling and reuse. Many of the indicators can be broken down to uncover even more data about the material but there is no standard way of doing so yet.

7.4 MATERIAL BANKS – DATA MANAGEMENT

In the context of the process map in Figure 19, this chapter portrays the area of interest #1 and all the subsequent points in the workflow that mention material banks.

Storing data on building materials and components is a crucial part of implementing circular economy principles into construction projects. One of the key issues derived from the literature review and data collection is the question of how to store data throughout the entire building lifecycle and onwards in an easy-to-access, secure way while still maintaining quite low storage volume. Material Banks allow for long-term storage of building data while organizing the transfer of material and component data from deconstructed buildings to new buildings. (Cai and Waldmann, 2019)

Implementation of Material Banks should happen at the national level, while the input, storage and maintenance of data can be managed by the municipality. A new managerial role of a “Material Bank Manager” could be introduced at the municipality whose responsibilities would include the input of data into the database as well as managing and upkeep of said data. The requirements for the role should involve knowledge of the specified querying to be able to manipulate data within the database. This role is inspired by the research by Honic et al., (2019) where a role of a material passport consultant is introduced. The authors specify the consultant role to have, among others, responsibilities of generating a MP, integrating recycling and LCA related data into the BIM process by making a link between databases, material inventory and analysis tool and also managing the data by allocating it to the appropriate building elements. Honic et al., (2019) propose that since the consultant manages material data, he should have knowledge about construction materials and their recycling potentials and environmental impacts. As for the material bank manager role presented in this chapter, his responsibilities exist more on the technical level (database knowledge) rather than the building/material composition and he would not have to possess any knowledge on construction materials.

The relational structure of the proposed municipality Material Bank database is shown on Figure 20. The database structure which is a part of the solution to this report is organized through the label property graph model which contains nodes and relationships between them, while nodes contain properties. Graph database is suitable to portray the material bank for storing material passport as component information as it is the best way to represent and query connected data (Robinson, Webber and Eifrem, 2015). The database structure portrayed through the graph is modeled in Neo4j Desktop graph database software. To manipulate and query the data from the graph database, modelled within the software, Cypher language is used. Cypher is an expressive query language intended to ease the process of retrieving the data for the stakeholders (Ian Robinson et al., 2015). The database includes many properties and their relation to the building material and therefore requires a database management system that gives relationships a high value. (Ian Robinson et al., 2015)

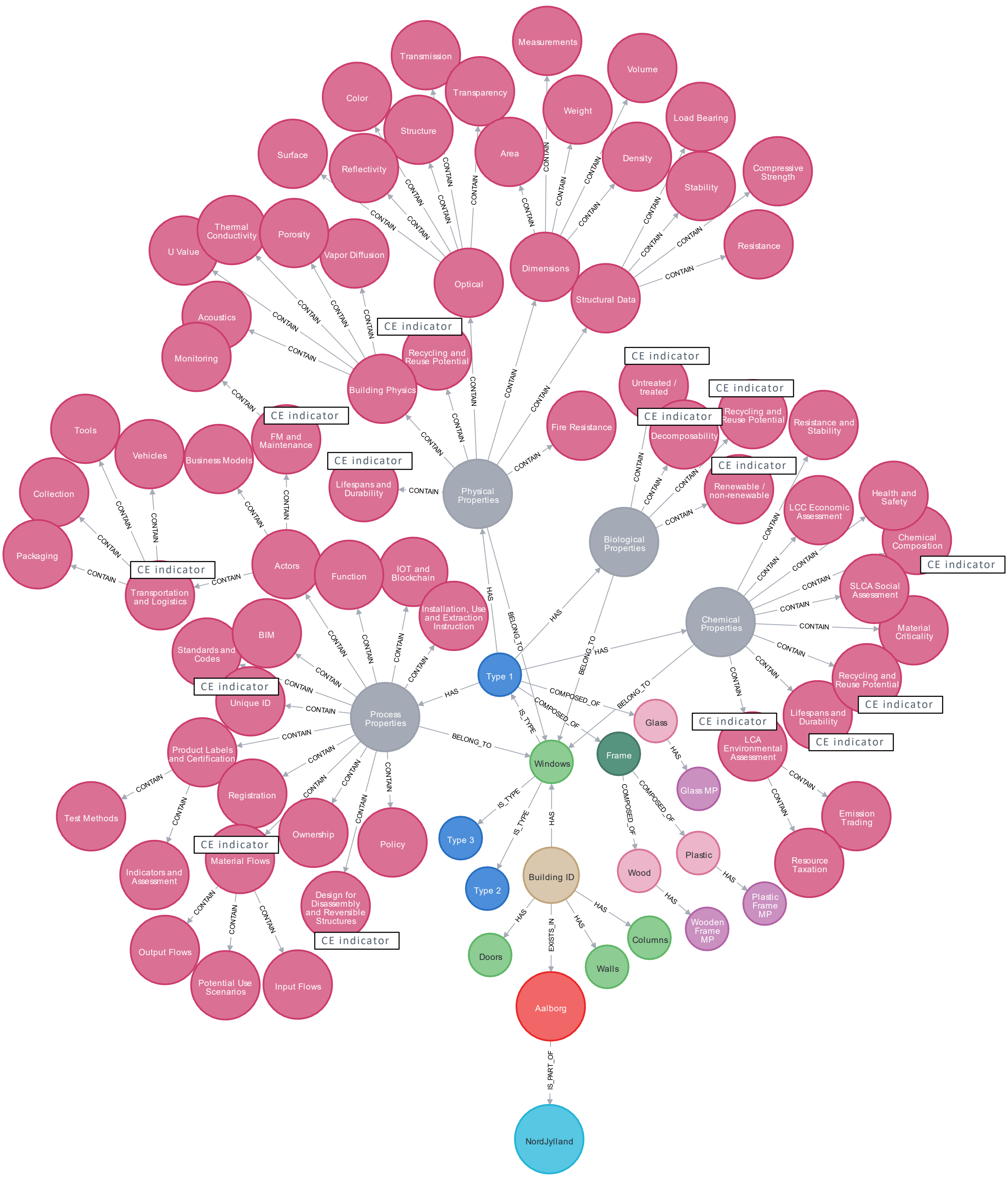


Figure 20 Label Property Graph for Material Bank Database (own illustration)

As specified in chapter 2.4.2 the CE related indicators must be included in the MP in order to create a tool able to handle data management for all kinds of environmental assessments e.g., LCA, circularity level. Following Heinrich and Lang (2019) the CE indicators are recognized to be:

- Physical Properties – Lifespan and durability, Recycling, and reuse potentials.
- Chemical Properties - Chemical composition, LCA, Lifespan and durability, Recycling, and reuse potential.
- Biological Properties – Decomposability, Renewable/Non-renewable, Treated/untreated, Recycling and reuse potential.
- Process Properties - Unique Identifier, Material Flows, DfD, Actors (Transportation, FM and maintenance).

7.4.1 Database Querying

To query the data from the database requires specific knowledge in graph databases, therefore to ease the process some pre-defined queries can be developed to exclude the need of Cypher commands (Ismail et al., 2018). The MB database is set around the components, since they are easiest to track within the industry and have much higher value of reuse in comparison to breaking the components down to the raw materials for recycling (Luscuere and Mulhall, 2017).

To portray queries that could be performed on the database, a smaller section of the label property graph was taken showing only a small part of what the Material Bank database would store. More specifically, the graph section on Figure 21 shows one physical property (lifespans and durability) and one biological property (treated) of one type of window (Type 1) within a building. In this case, the lifespans and durability property would give a numerical value of years, meaning how much the lifespan of the specific window is, and the treated property would give a value of “yes” or “no”, meaning if the window has been treated with any substances.

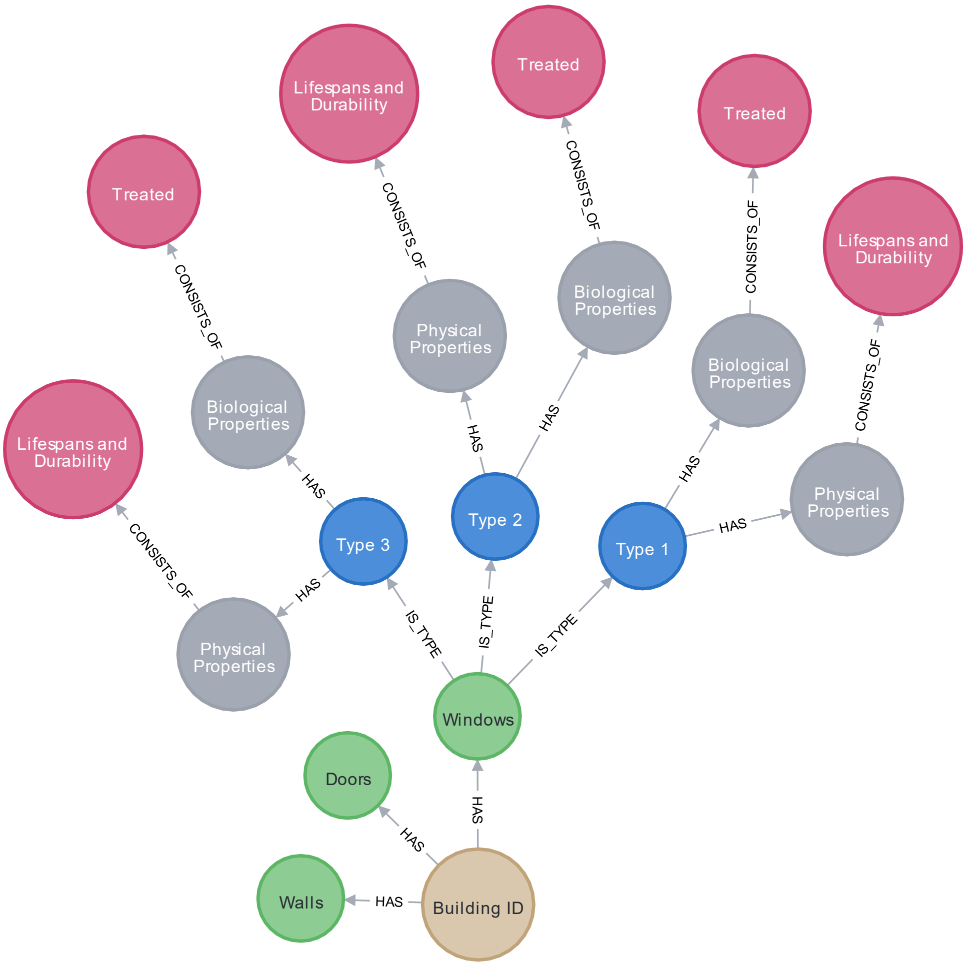


Figure 21 Label Property Graph section (own illustration)

Below are examples of queries that could be run on the label property graph on Figure 21. These queries represent examples of what values the user could extract from the database and how.

In order to understand the values behind the physical property of “lifespans and durability” and the biological property of “treated”, a simple query can be run portraying these values and which window types they belong to. The query would be scripted as following:

MATCH (lifespan{name:"Lifespans and Durability"})<-[CONSISTS_OF]-(physicalprop{name:"Physical Properties"})-[:HAS]-(windowtype) RETURN windowtype.name AS name, lifespan.lifespan AS lifespan

This type of query would be useful if the user is trying to view the lifespan of all the components (in this case windows) within a building. Lifespan is an important indicator of circular economy, since by the lifespan the user can determine whether the component is suitable for the next building project or not, according to how many years it has left of its lifespan since it was first installed.

"name"	"lifespan"
"Type 1"	"30"
"Type 3"	"45"
"Type 2"	"35"

MATCH (treated{name:"Treated"})<-[CONSISTS_OF]-(biologicalprop{name:"Biological Properties"})-[:HAS]-(windowtype) RETURN windowtype.name AS name, treated.treated AS treated

By this query, the user can view which components have been treated – and is able to figure out which components include materials that could be treated with any chemical substances. This indicator is important to circular economy and future component reuse options as materials that are chemically treated can pose a risk to health and the environment and might have to be landfilled or thermally incinerated. (Heinrich and Lang, 2019)

"name"	"treated"
"Type 1"	"yes"
"Type 2"	"yes"
"Type 3"	"no"

In a scenario when it is necessary to use windows that have a lifespan of at least 40 years, the user can try to run a query by asking a question: Which window types have a lifespan of more than 40 years?

MATCH (lifespan{name:"Lifespans and Durability"})<-[CONSISTS_OF]-(physicalprop{name:"Physical Properties"})-[:HAS]-(windowtype) RETURN windowtype.name AS name, lifespan.lifespan>"40" AS lifespan

"name"	"lifespan"
"Type 1"	false
"Type 3"	true
"Type 2"	false

Types showing a result of “false” have a lifespan of less than 40 years and types showing “true” have a lifespan of more than 40 years.

And, similarly, the user could ask a question: Which window types are treated? The query can be written to get the results of all window types that biological property "treated" equals yes and results will come in a true/false value.

```
MATCH (treated{name:"Treated"})<-[CONSISTS_OF]-(biologicalprop{name:"Biological Properties"})-[:HAS]-(windowtype) RETURN windowtype.name AS name, treated.treated="yes" AS treated
```

"name"	"treated"
"Type 1"	true
"Type 2"	true
"Type 3"	false

All types with the result "true" under the treated property have been treated and all with result "false" have not been treated.

7.4.2 User Interface

The proposed material bank database could be implemented into a website that already gathers some information about existing buildings in the whole country. Such website in Denmark is the Danish Building and Housing Registry ("Bygnigs og Boligregistret," 2020) which includes some basic building data such as the year of execution, the building and plot size, materials of the outer wall and roof coverings and information about heating.

Since the user should not only be able to search information on a specific building but also by component types, the front page could include an option to choose by components. In order to portray how the user interface could look like with the material bank database implemented in the registry webpage, the example of material bank structure on Figure 21 is used. The current front page of the registry, where the user is able to search a building by address or property number has a setup as shown in the figure below.

Figure 22 Building and Housing Registry front page (Bygnigs og Boligregistret, 2020)

For the user to be able to search by specific building components, an option of choosing components and, more specifically, structural, and architectural components could be added to the front page of the Building and Housing Registry. The proposed front page would then look like the figure below illustrates.

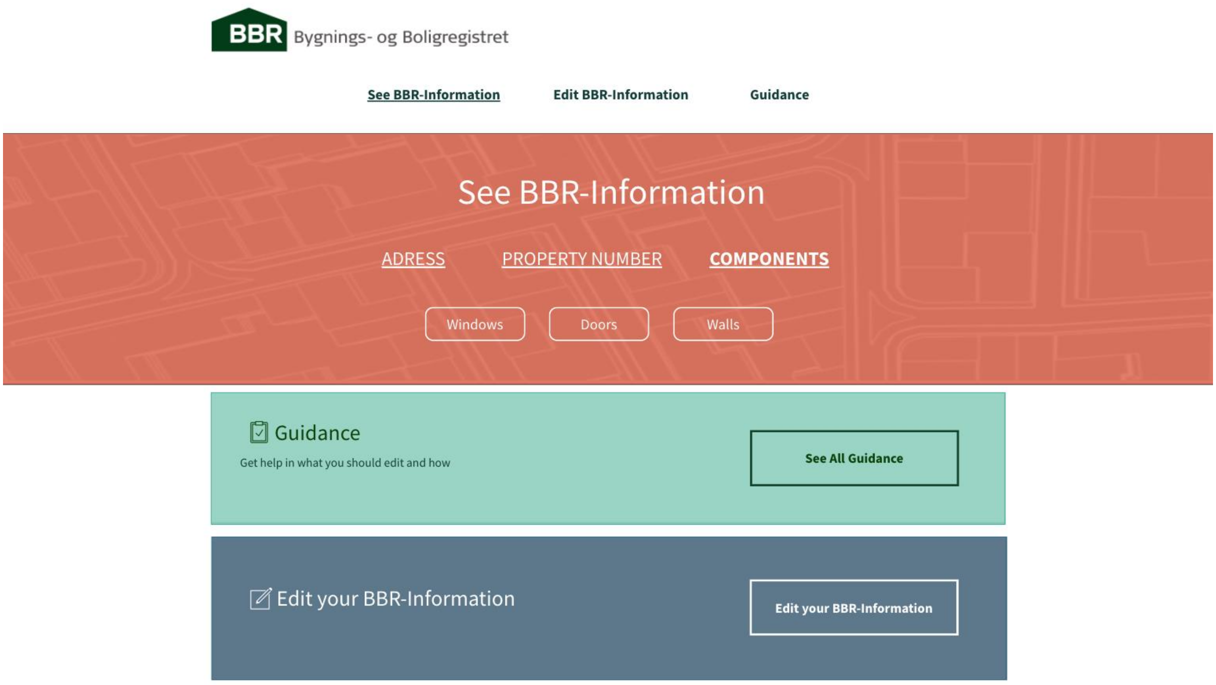


Figure 23 Proposed user interface - front page

Since using the graph database structure on Figure 21, we can choose “Windows” from the components option and could get a page such as portrayed on Figure 24. On this page the user could see all the different window types available to use in a new project (in this case Type 1, Type 2, and Type 3). These windows can be filtered by different attributes such as, in this example, Size, Lifespan and Treatment, but of course, all different attributes mentioned in chapter 7.2.2 of this report can be used here to get a list of the desired component types.

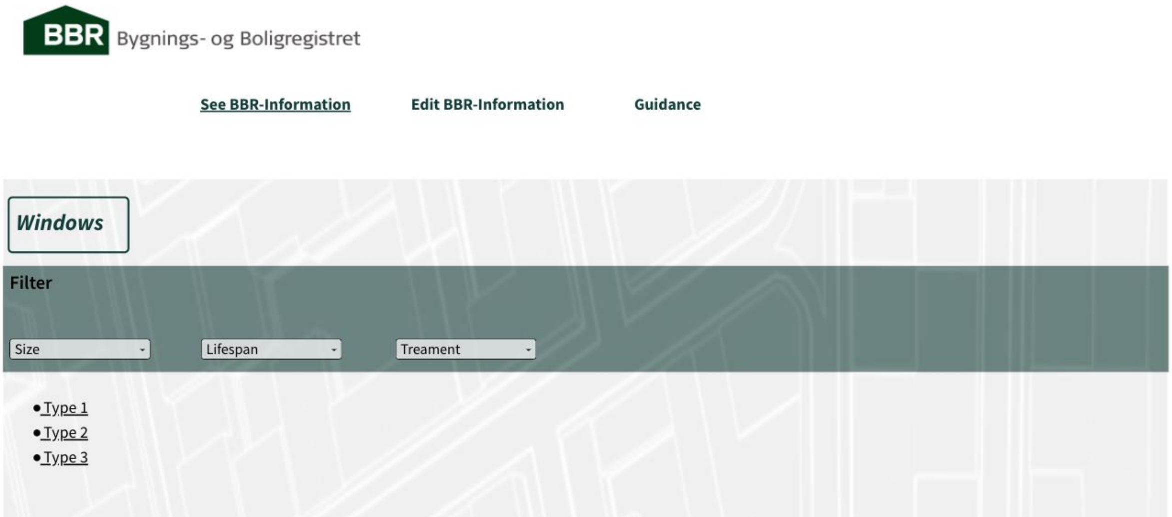


Figure 24 Proposed user interface - Component page

The existing building data on the Building and Housing Registry webpage is available to download in a pdf format and looks as following:

Matrikelnr.: 70a
Beliggenhed (kvalitet): Sikker
Antal etager u. kælder & tagetage: 4
Antal helårsboliger uden køkken: 0

Landsejerlavsnavn: SDR. TRANDERS BY, SDR. TRANDERS
Opførelsesår: 2018
Antal helårsboliger med køkken: 0
Afvigende etager: Bygningen har afvigende etager

Materialer
Ydervæggens materiale: Metal
Tagdækningsmateriale: Tagpap med lille hældning
Kilde til bygningens materialer: Oplyst af ejer (eller dennes repræsentant)

Areal i grundplan	**m2**	**Samlet andet areal**	**m2**	**Bygningens arealanvendelse**	**m2**
Bebygget areal	2343	Samlet andet areal	0	Samlet boligareal	0
Overdækket areal	0	Heraf affaldsrum i terræn	0	Heraf areal af lovlig beboelse i kælder	0
Areal i hele bygningen	**m2**	Heraf indbygget garage	0	Samlet erhvervsareal	9283
Samlet bygningsareal (excl. kælder & tagetage)	8058	Heraf indbygget carport	0	Heraf erhverv i kælder	0
		Heraf indbygget udhus	0	Antal etager u. kælder & tagetage	4
Samlet kælderareal	1225	Heraf lukkede overdækninger	0		
Heraf udnyttet kælder	0	Heraf indbygget udestue el. lign.	0		
Heraf dyb kælder	1225	Heraf udvendig efter isolering	0		
Samlet tagetageareal	0	Heraf øvrige arealer	0		
Heraf udnyttet tagetage	0	Heraf indbygget garage i kælder	0		

Kilde til bygningsarealer: Oplyst af ejer (eller dennes repræsentant)

Energioplysninger
Varmeinstallation: Fjernvarme/blokvarme
Supplerende varme: Solpaneler

Figure 25 Building and Housing Registry Building Data (Bygnigs og Boligregistret, 2020)

Similarly to how the data about buildings from the registry as portrayed on Figure 25 can be downloaded, the user could get a material passport in a pdf format when selecting a certain component type. Therefore, it would be possible to review the component in more detail by viewing all the attributes including circular economy indicators and the background of the component to find out whether the component is suitable for a project.

7.5 PRELIMINARY LCA

The preliminary LCA processes are portraying the area of interest #2 from Figure 19. The new workflow promotes the MP as main data input for LCA, thus solves the problem described in chapter 7.3 in terms of information input from different databases with different ontologies and indicators for CE. Since many tools and processes already exist for these analyses, this approach could improve standardization of indicators for assessment of environmental impact and circularity among large stock of buildings.

The preliminary LCA should be carried out together with pre-environmental assessments (e.g. German Sustainable Building Council - DGNB) as early as possible and in accordance with existing standards (see 7.2, Table 5). Since information about the materials composition has a significant influence over the potential environmental impact and depends on the number of reuse cycles (Eberhardt et al., 2019), the data from MP improves greatly the validity of the LCA and the quantifying capabilities of implementing CE principles.

The process map highlights integration of MB database with BIM tools to access the data required for the LCA in connection with specific design options. At the same time, the model is not overload with semantic data.

7.6 INPUT OF MATERIAL BANK DATA

The area of interest #3 in the process map of the workflow (Figure 19), shows the requirement of inputting data into the MB. But before projects like this can be put in place, there must be an established database with sufficient amount of building projects to choose from for the proposed workflow, incorporating data retrieval from a Material Bank. Therefore, it needs to be specified what existing buildings are selected as primary datasets to start building the database and subsequently a standard process for input of new build projects under design/construction needs to be determined. This chapter foreshadows the possibilities of how that can be achieved.

7.6.1 Data Input of Existing Building

There are many buildings in operation and digitalizing them all for input to material banks is simply not possible. With the process of creating digital data for existing building being very time consuming in terms of collecting, processing and storing large amount of data (Heinrich and Lang, 2019), for many buildings that have poor level of information, the relation of time spent versus the gain is not worth. It is necessary that prior to creating a dataset for an existing building a mapping technique is in place that would efficiently analyze the potential of the building being digitalized to a level of information data sufficient for the material bank. For example, it would be a good idea to look at DGNB certified buildings (or other certifications systems for that matter, depending on the location) as products that are well documented and have high potential for success. Another example of mapping out buildings that it would be wise to proceed with is introduced in a master thesis by a fellow student Erling Vånge from Aalborg University. His research concluded that buildings with the most repetitive patterns would be the most fitting to proceed with mapping. To find the patterns, the thesis proposes a mathematical formula that contains variables describing the building features, to determine the 'repetitive score' of buildings (Figure 26).

$$R_s = A_d + \frac{\frac{B_c}{2} + 5E_a + 5B_g - 2C_h}{100}$$

$$\text{where } 0 < R_s < 2$$

$$\text{and } A_d = \frac{V_r}{S(V_t)}$$

Variable	Description
R_s	R-Score
A_d	Architectural Style and Design
B_g	Generic Estimate
C_h	Health Grade
D_a	Building Age
E_a	Accessibility Rate
V_r	Volume of repetitive components
V_t	Total volume of components

Figure 26 Repetitive score for decision making of mapping existing buildings (Vånge, 2020)

Additional important feature of the buildings with repetitive patterns is the buildings' level of documentation, that dictate the overall cost of the mapping (Vånge, 2020). The certified buildings must have a good level of documentation and transparency to be reach the certifications, therefore, the combination of this approach of the repetitive score together with investigating sustainably certified buildings could be the way to proceed.

7.6.2 Data Input of New Building Projects

Once a primary dataset in the MB is established and new circular projects are created according to the proposed workflow, all the projects come across a point in the timeline where it is required to contribute to the MB database with components and materials of the new building. A fitting phase for the task is determined to be the Technical Design, where the building's model is in state ready for construction. Furthermore, this task should be tied to a checkpoint of the project process, therefore it is suggested that the building content with sufficient information is provided to the MB at the stage of applying for building permit, where one of the building permit conditions is the contribution to the MB. For this purpose, a development of new standard is proposed (EN NS1-3:2021 - Table 6) that would contain specifications to facilitate this process.

7.7 CE GATEWAY PHASE ASSESSMENT (CEGPA)

As previously described and supported by the literature review and the interviews conducted, the transition between project stages is insufficient regarding general goal congruency of involved parties, thus defying the core principles of CE. Such silo-approach leads to loss of data, un-coordinated design, and communication difficulties, resulting in reactive measures to fix problems. This involves transitions between the main project phases, like design to construction, but also design sub-phases explored in this research.

To eradicate information loss, smoothen the workflow and, therefore, promote the CE model in construction projects, we propose the workflow process map (chapter 6) to be further facilitated with CEGPA for each of the phases (**Error! Reference source not found.**).

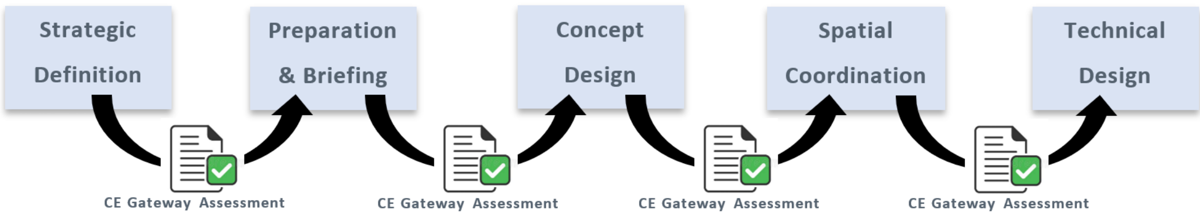


Figure 27 CE Assessments as gateways to bridge project phases (own illustration)

These assessments (reflecting the five pillars: CE knowledge, BIM expertise, collaboration, early design, and standardization) work as gateways to individual project phases, where the project cannot move further until the assessment is done. The assessment itself is in form of a check list that needs to be fulfilled in its entirety in order to proceed to next stage of the project and the items are based on the 2020 DGNB award criteria (DGNB GmbH, 2020) together with CE incentives and enablers collected from the reviewed literature. Standards referred to in the checklist can be found and described in 7. Proposed Solution.

7.7.1 Checklist of Tasks: Strategic Definition to Preparation & Briefing

Circular Economy

Sustainable Responsibility

☐ Client pledges corporate responsibility of sustainable raw extraction according to standard EN NS3:2021

☐ At least five technical systems for passive building concept are described in the strategic definition phase (fx. cooling, heating, daylight, ventilation, building envelope etc.)

☐ Plan to achieve the energy demand of the building from renewable sources is in place

☐ At least 10% of the total energy usage of the final design can be contributed from surrounding institutions / users.

☐ Mobility sharing parking spaces (cars, bicycles etc.) are located within close reach (max 500m radius)

Building space efficiency and modularity

☐ Rooms and their purpose are clearly defined and argued for

☐ Repurposing approaches are defined (fx. non-load bearing partitions, building expansion without modifying the structure)

☐ Modular elements are part of the requirements

Integration of service models

☐ One or more service models are proposed for operation (fx. carpets, lighting, elevators)

Reuse of materials, components, or structural elements

☐ Goal of reused structural & architectural elements from existing buildings is stated (minimum per standard EN NS3:2021)

☐ Goal of reused Mechanical/HVAC elements from existing buildings is stated (minimum per standard EN NS3:2021)

☐ Life span of the building is specified and design for disassembly required. Slack of 10 years is allowed.

Energy generation

☐ Plan for excess energy use is in place (if applicable)

Collaboration & Building Information Modelling (BIM)

Stakeholders

☐ The client and design teams are appointed with necessary specialists (as per standard EN NS3:2021)

☐ All stakeholders have access to project information as per point above

Exchange platform

☐ The choice of an exchange platform is clearly defined and argued for

☐ All stakeholders have access to all the exchanged data at the platform (not necessarily editable access, but viewable)

☐ Unique access keys are defined for different actors according to data accessibility

Integration of BIM

☐ Plan for use and updating of BIM data is in place

☐ Software and tools to be used are specified by all the appointed parties

☐ Collaborative interoperability of items specified in 2.1.2 is verified (means of export/import file formats)

Integration of Material Bank (MB) & Material Passports (MP)

☐ Plan for retrieving and inserting data from/to MB is in place. (see process map Figure 19)

☐ Responsible actor/party is assigned for retrieving relevant data from the MB at specified stages

☐ Responsible actor/party is assigned for inserting relevant data to the MB at a specified stage (according to standard EN NS1-3:2021)

☐ Material Bank of existing building is accessed to support availability for the points

Early Design Decisions

Integration of life cycle assessment (LCA) & life cycle costing (LCC) to the building project

☐ An LCA & LCC plans is prepared at the strategic definition phase (including construction, operation, and end-of-life)

☐ Short description of methodology and scope for the analysis is presented

☐ LCA results are demanded at intervals as shown in the process map above

☐ At least three different specialists are included in the LCA integration (structural engineer, MEP engineer, energy engineer etc.)

Environmental certification system

☐ A chosen environmental certification system is clearly determined and argued for

☐ A target certification according to chosen system at previous point is stated (must be higher than mean value, i.e for DGNB system the goal must be gold or higher)

☐ LCA results are demanded at intervals as shown in the process map above

Standardization

Use Standards

☐ Processes are compliant with relevant standards as specified in the process map (Figure 19)

7.7.2 Integration to the project platform

The assessment document could be altogether done in form of a physical checking and approving by a single responsible person but integrating it to the BIM process and the exchange platform selected is more appropriate. We propose the phase assessment to be a multi-disciplinary assignment, where stakeholders have relevant responsibilities assigned to fulfill, fx. a sustainable consultant to choose a sustainability certification system or the client to define the purpose of demanded rooms in the project. The individual points of the checklist presented previously are all supported with extra information and standards (**Error! Reference source not found.** – Information & Attachments tabs) to comply with a bout the specific task to ensure user friendliness of the process.

For technical data like number of reused materials or LCA results, the checklist is essentially a set of rules that can be fulfilled automatically by relevant information being uploaded/exchanged/present on the collaborative platform database for the project. Each tasks or group of tasks also has a responsible stakeholder assigned for achieving the task by providing the relevant information. (see Example 1 – Technical Data). For semantic data like pledging sustainable responsibility or choice of certification system, the fulfillment can be done in similar fashion as the technical data by uploading the correct documentation and fulfilling relevant rules or by agreeing to specified terms & conditions for the respective task. (see example 2 – Semantic Data)

Example 1 – Technical Data: The Spatial coordination phase is about to transition to the technical design phase and one of the tasks to proceed is a completed LCA analysis by the sustainability consultant. The task will be checked as done once the set of rules tied to the task is fulfilled (Figure 28).

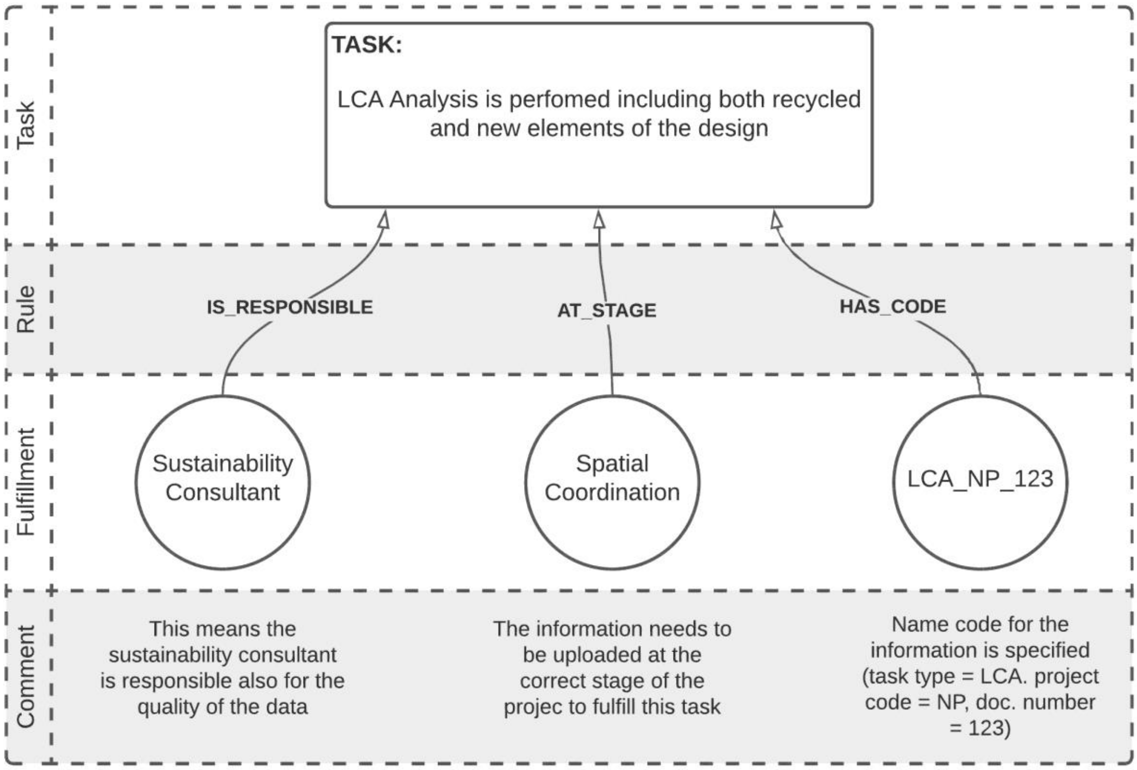


Figure 28 Task completion by set of rules (own illustration)

Example 2 - Semantic Data: The strategic planning phase is about to transition to the preparation and briefing phase. One of the tasks is for the client to plead sustainable responsibility specified in document ''Responsibility of Sustainable Raw Extraction – Pledge'' (**Error! Reference source not found.**).

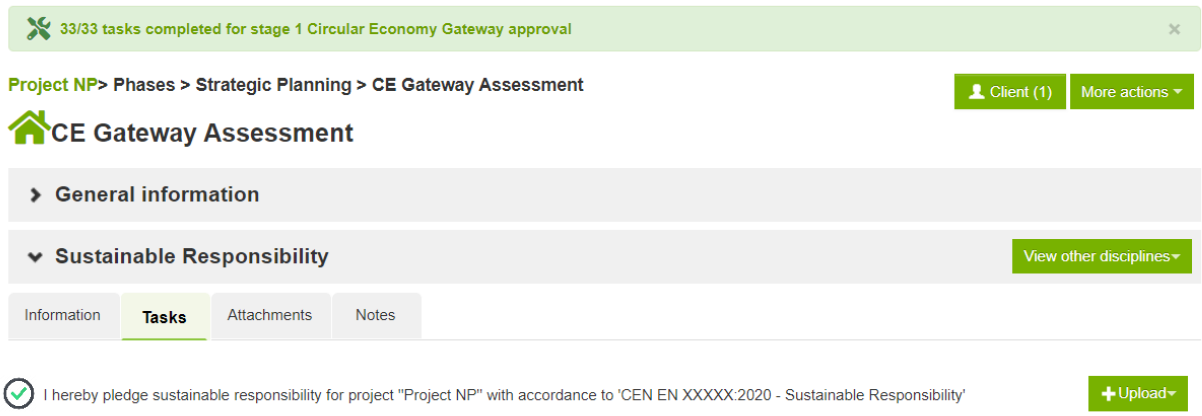


Figure 29 Example of a rule from the checklist integrated to the collaborative platform (own illustration)

The gateway assessment between phase transition is implemented to facilitate the process toward CE practices. The checklist tackles the silo-approach problem, by ensuring preparation of phases in a way that the next stages can smoothly follow up on the work and knowledge is shared. As a result, the circular project links between phases are tightened for data loss and bridge for effective transitions. Furthermore, the gateway assessment demands the project stakeholders to incorporate circular and sustainable tactics into building projects.

7.8 SOLUTION SUMMARY

The approach to creating the solution is systematic by design, building on the five pillars (Figure 15) derived from the data collected by literature review and interviews with construction professionals. With this as a base, a new workflow for building projects is proposed, incorporating BIM expertise, CE approaches, standards, and collaborative techniques in the early design phases, to support the industry move towards CE. The workflow portrayed as a process map serves project stakeholders as a standard to follow, helping them to track project requirements and project progress with a goal of a designed circular building. Showing the general workflow proposed for implementation, the solution further expands into describing four areas within the process map.

The first area of interest explains the MBs and MPs more in depth. The content of both MBs and MPs is explored to determine what relevant information they need to include how are they structured. To elaborate on that, structure of the MB database is created as a label property graph using neo4j. To bring closer the user interaction with the MB, and example query is performed, and user interface mock-up is created.

The second area of interest promotes the BIM-integrated LCA usage early on, where the information in the MPs serve as the primary datasets for performing the analysis. Consecutively, the performed LCA results are urged to be used with sustainability pre-assessment (fx. DGNB) to be aware of the environmental impact potential of the project at early stages.

The third area of interests touches the surface on suggestions to MB data input, tackling the problems of creating primary datasets from existing buildings and specifying data quality and input of new building projects.

The fourth area of interest introduces the CEGPA for facilitation of phase transitions. The checklist, developed from DGNB' KPIs and CE indicators collected through literature review, ensures better collaboration between stakeholders for goal congruency, smooth phase completion and transition, and circular responsibility assigning. The circular and sustainable approaches are demanded for project progression by the CEGPA and supported by project standards

The proposed solution, namely the workflow and the CEGPA, is then further refined and brought to its final form according to the feedback session conducted with industry professionals.

CHAPTER:

8. FUTURE DEVELOPMENT

This chapter describes the work within the solution that lies ahead to tackle its limitations. Some of the ‘future development’ points arise naturally, as the scope of the working solution in practice extends far beyond the project scope of this thesis. Other part of the points emerge from a brainstorming session after the solution is completed. Final part of the ‘future development’ points emerge from the feedback session with industry professionals.

The proposed solution, as expected, has number of limitations that are mainly the outcome of limited time this master thesis has assigned but also some aspects of it are far beyond the scope of the project and expertise of the students. These identified limitations are worked in the points of future development, which are reflections of the solution limitations.

- **User Environment Testing**

Looking at the possibility of the solution being implemented onto construction projects, a thorough and lengthy testing with industry professionals is crucial. The solution as it stands now does not contain its implication on the users in any way. For the solution to be sold/marketed several parameters of the various parts, fx. time it takes to fulfill the CEGPA, need to be stated as proof of concept. Therefore, before the solution can be presented as a tool, engineers, architects, clients etc. need to spend few weeks using it and reporting back.

- **Development of the Process Map UI**

One of the outcome points of the feedback session with industry professionals to refine the solution was the necessity of updating the UI of the workflow. The current state of the process map is very detailed and its function to map out the workflow works as it should for this purpose. For the purpose of implementation, however, it was noted that it needs to be more clear, visual, and user friendly. This does not also include any front-end solution to the proposed workflow, nor does it specify the user interaction with it.

A suggestion for the future development in that sense came from our interviewees, where they suggested simplifying the processes to just simple tiles with task description. In order to still achieve conveying the information through to the user, enhancing the process map with interactive features (information showing when hovering over objects, possibility to expand on selected items) is to be further developed.

- **Societal Links Within Circular Economy Approaches**

The focus of this paper was given to the processes, requirements and standards needed to be developed for successful implementation of circular economy into construction projects. However, when implementing any kind of changes especially, such as in this paper, ones that alter existing processes while implementing technology, the mindset of the people is an important factor to keep in mind. Therefore, the societal links or techno change perspective could be investigated to further develop this research. As Henderson and Ruikar, (2010) state in their research, the construction industry is subjected to high degrees of fragmentation due the lack of unity when implementing new ways and technologies which can lead to resistance and the industry lacking in progressivity compared to other industries. The authors also made several recommendations to the industry on the implementation of technology and the effect it has on people within organizations, which could be further evaluated and applied to the development of this research.

- **Technical Aspects of Data Linking**

A possible topic to investigate with future development of this research is the technical aspects of linking building and component data into the material bank database. The research performed in this report focuses mainly on processes and data input requirements for the database as this was determined to be a crucial point from literature review and interviews, however a development can be made in this area by exploring how the actual data input and linking could happen within the BIM environment. In future research focus could be given to data file formats and how they could be linked together in an easy and automated way to avoid data loss in transfer.

- **Development of new standards**

Development of new standards provides a well needed push towards the CE implementation, thus establishing the CEGPA standards for the new workflow is just a first step in the direction of standardised circular processes in the AEC industry. Governmental viewpoint and awareness on CE play an important role in this course of action, to bring more attention to the possibilities of circularity and enhance the research progress concerning the new standards.

- **Other project stages**

Development of the CEGPA for stages not included in this study could help bridging the gap between BoI and EoL of projects and buildings and enhance improvement of methods for assessing the usability of building parts in other projects. The coherence between both project stages and buildings elements life cycles is an important part of the future work towards the holistic approach to the AEC circular projects.

- **BIM integrated LCA**

Further development of means of linking the semantic data with BIM and LCA could advance the automation of procedures, thus eliminate the human error factor. Following the approach of this study, the data input for both BIM and LCA can be furthered scrutinized to lead to potential improvements and coherence of CE indicators.

CHAPTER:

9. CONCLUSION

This chapter wraps the thesis report in a short summary and conclusion, attempting to answer the main problem formulation question, as well as all the sub-questions that have been drafted in Chapter 5. Problem Formulation

Being at the top of the list of industry polluters, the building sector needs prompt initiation and immediate transition towards environmentally friendly solutions. The current techniques of project development are inefficient and wasteful, and the outcome of this master thesis seeks to lead new building projects towards increased sustainability by design. The aim of this research is to identify and analyze the common practices and workflows within the current state of the construction industry, to find out how can BIM support refinement of the processes and responsibilities to enhance Circular Economy approaches during early design phases.

The academic contribution by creating a solution to this problem formulation, lies on a solid five-pillar foundation derived from the systematic literature review and interviews with construction industry professionals. The review of literature works contains analysis of BIM & CE currently represented in the AEC, BIM-LCA tools, and sustainability assessment methods, displaying the state-of-the-art sustainability techniques in the sector and academic research. The interviewee's professions, including engineers, architects, BIM consultants, sustainability specialists, and PhD researchers, further expand on the actual uses and practices of the aforementioned sustainability techniques as the questionnaire reflects the literature search.

The five pillars (CE Knowledge, BIM Expertise, Early Design, Collaboration, and Standardization) that are drawn from analyzing the collected primary and secondary data are the fundamentals allowing project implementation of CE models. With that as the outset, the solution is built on the determined pillars to answer the problem formulation:

''How can BIM support early design processes to enhance Circular Economy approaches within building projects?''

The solution, in form of a process map, is a proposed new standardized workflow for circular building projects that is supported by BIM tools and techniques. When project stakeholders follow the designed steps of the workflow, BIM allows the early design processes to be smooth in collaboration, transparent in information exchange, and organized in responsibilities, while having the relevant data structured and accessible. All these points, together with extra demands on CE fulfillments, support the enhancement of CE approaches within building projects.

Implementing such broad and multi-layered solution, results in adjustments among a lot of professional areas within the industry, the scope of this project further touches on few of them. The new workflow promotes the change of course for the early design stages in order to incorporate the CE principles. This step allows to address the effect of this change on existing processes in theses stages of projects.

The new process map and literature review proves the current processes in the design phases in the AEC industry to be insufficient in terms of supporting the turn to the CE enhanced projects. Integrating the CE principles into early design pushes the existing processes towards better collaboration between the stakeholders by opening new channels of communication and forming a common platform for data input in form of MB. This integration of circularity allows for improved overview of building parts life cycles and their environmental impact but requires changes in the mindset and general approach to the means of handling the transition between the project stages.

The study stimulates the CE integration by adding to the shift of focus of the early design procedures regarding the design approaches, reuse capabilities, health of the materials and the means of storing and updating the data. Due to large amount of CE related data circulating within the AEC projects and stakeholders the methods of handling the exchange and storage processes in the BIM environment needs to be addressed.

The implementation of new circular economy approaches into construction projects comes with a variety of new building component and material data that needs to be handled in a user-friendly, accessible way and, most importantly, in a way where no data is lost in storage and transfer and can be upkept during the entire building lifecycle and onwards. Material and component properties are stored within the BIM environment in material passports which come with specific requirements on indicators and properties that need to be provided by manufacturers – this ensures that all information about a product needed for future reuse is available.

Once the material passports of each building element are gathered, they are stored in a material bank database to ensure a secure upkeep of data which is openly available and has a foundation in the Danish Building and Housing Registry for which a simple user interface is defined in this project. The data is managed by the municipality in which the project exists and, more specifically, the new managerial role proposed in this report – the material bank manager, which results in a clear and smooth process of data upkeep and an understandable responsibility for said data.

Having building data and detailed information on materials and components stored in the material bank database and openly available to view and download by the design teams of new construction projects should improve the initial choice of reusable materials in the strategic definition phase to fit each new construction project and, therefore, aid towards an increase in motivation to reuse building components.

Easy access to data is not the only part of the process that keeps stakeholders engaged and motivated to participate in circular projects. A very large aspect of circularity implementation and stakeholder involvement is the overall coherent run of the projects, therefore the shift between different construction project phases is addressed.

Ensuring smooth transition between phases, that has been a reoccurring problematic within the reviewed literature, is incorporated as a feature of the new workflow in shape of a gateway assessment that demands CE responsibilities, intended to be BIM compatible. To eradicate information loss, smoothen the workflow and, promote the CE model in construction projects, CE Gateway Phase Assessment (CEGPA) is a checklist developed to be applied at every project phase transition. The checklist, created from DGNB' KPIs and CE indicators collected through literature review, ensures better collaboration between stakeholders for goal congruency, smooth phase completion and transition, and circular responsibility assigning. As a result, the circular project links between phases are tightened for data loss and bridge for effective transitions.

Overall, there is no doubt that implementing such a large concept as Circular Economy into construction project comes with numerous amounts of alterations to known processes and common practices and there are many aspects of the construction process that need to be addressed from the early design phases of the projects. Issues such as the need for standardization, stakeholder involvement and collaboration and a coherent and smooth project run are determined to be crucial. This research contributes to the industry by proposing a framework addressing all the pivotal challenges, needs and requirements for a successful implementation of circular economy into construction projects while utilizing BIM as a commonly known and utilized tool within the AEC industry in hopes of a move from linear towards circular building projects soon.

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Velasquez, C.V., Salehi, N., Hallstedt, S.I., 2020. HOW CAN INFORMATION AND COMMUNICATIONS TECHNOLOGY SUPPORT THE LINK BETWEEN CIRCULAR ECONOMY AND

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APPENDIX

A.1 1st Literature Screening

Item Type	Author	Title	Date	Dawid	Michaela	Simon	DECISION
conferencePaper	Buhl, Henrik; Andersen, Michael; K	A "Knot"–breaking the inertia in construction?	2017				
conferencePaper	Di Biccari, C.; Abualdenien, J.; Borr	A BIM-based framework to visually evaluate Circularity and Life Cycle Cost of buildings.	2019				
journalArticle	Oti, A. H.; Kurul, E.; Cheung, F.; Tah	A framework for the utilization of Building Management System data in building information models for building design and operation	2016				
journalArticle	Rezgui, Yacine; Beach, Thomas; Ra	A GOVERNANCE APPROACH FOR BIM MANAGEMENT ACROSS LIFECYCLE AND SUPPLY CHAINS USING MIXED-MODES OF INFORMATION DELIVERY	2013				
journalArticle	Chong, Heap-Yih; Lee, Cen-Ying; W	A mixed review of the adoption of Building Information Modelling (BIM) for sustainability	2017				
journalArticle	Zou, Yang; Kiviniemi, Arto; Jones, S	A review of risk management through BIM and BIM-related technologies	2017				
journalArticle	Osobajo, Oluyomi A.; Oke, Adekun	A systematic review of circular economy research in the construction industry	2020				
journalArticle	Bolier, Marc	Accelerating the transition towards circular economy within the built environment: Utilizing blockchain technology and designing a circular, modular, temp	2019				
journalArticle	Rogers, John; Chong, Heap-Yih; Pre	Adoption of Building Information Modelling technology (BIM)	2015				
journalArticle	Vilutiene, Tatjana; Hosseini, M. Re	Advanced BIM Applications in the Construction Industry	2019				
journalArticle	T V Nguyen; E K Amoah	An Approach to Enhance Interoperability of Building Information Modeling (BIM) and Data Exchange in Integrated Building Design and Analysis	2019				
journalArticle	Jalaei, Farzad; Jalaei, Farnaz; Moha	An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects	2020				
conferencePaper	Daniotti, Bruno; LUPICA SPAGNOLO	An Italian BIM-based portal to support collaborative design and construction	2017				EXTRA RESOURCES
journalArticle	Ding, Lieyun; Xu, Xun	Application of Cloud Storage on BIM Life-Cycle Management	2014				EXTRA RESOURCES
journalArticle	Mohammed, Abdullah Badawy	Applying BIM to achieve sustainability throughout a building life cycle towards a sustainable BIM model	2019				
book	Rios, Fernanda Cruz	Beyond Recycling: Design for Disassembly, Reuse, and Circular Economy in the Built Environment	2018				EXTRA RESOURCES
journalArticle	Thomassen, Mats	BIM & Collaboration in the AEC Industry	2011				
journalArticle	Aguiar, A.; Vonk, R.; Kamp, F.	BIM and Circular Design	2019				
book	Hardin, Brad; McCool, Dave	BIM and construction management: proven tools, methods, and workflows	2015				
conferencePaper	Susanna Fulop	BIM AND MULTI-LEVEL COMPLEX CONSTRUCTION DATABASE FOR SUSTAINABLE DESIGN	2018				
document	Lévy, François	BIM and Sustainable Design	2011				
journalArticle	Jacobsson, Mattias; Merschbrock,	BIM coordinators: a review	2018				
journalArticle	Delgado, Juan Manuel Davila; Oye	BIM data model requirements for asset monitoring and the circular economy	2020				
journalArticle	Wu, Wei; Issa, Raja RA	BIM execution planning in green building projects: LEED as a use case	2015				
journalArticle	Suchocki, M.	BIM for Infrastructure: integrating spatial and model data for more efficient contextual planning, design, construction and operation	2015				
conferencePaper	Larasati, Dewi; Hanifah, Yulita; Wil	BIM Implementation to Improve Construction Work Performance	2020				
journalArticle	Kerosuo, Hannele	BIM-based collaboration across organizational and disciplinary boundaries through knotworking	2015				
journalArticle	Akinade, Olugbenga O.; Oyedele, L	BIM-based deconstruction tool: Towards essential functionalities	2017				
journalArticle	Akbarieh, Arghavan; Jayasinghe, La	BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review	2020				
journalArticle	Santos, Rúben; Costa, António Agu	BIM-based life cycle assessment and life cycle costing of an office building in Western Europe	2020				
conferencePaper	Guerriero, Annie; Kubicki, Sylvain;	BIM-enhanced collaborative smart technologies for LEAN construction processes	2017				
conferencePaper	Sebastian, R.	Breaking through business and legal barriers of open collaborative processes based on building information modelling (BIM)	2010				
journalArticle	Eberhardt, Leonora Charlotte Mala	Building design and construction strategies for a circular economy	2020				
journalArticle	Glema, A.	Building Information Modeling BIM - Level of Digital Construction	2017				
conferencePaper	AMALIA BANTELI; VICKI E. STEVENS	BUILDING INFORMATION MODELLING (BIM) AS AN ENABLER FOR WHOLE-BUILDING EMBODIED ENERGY AND CARBON CALCULATION IN EARLY-STAGE BUII	2017				EXTRA RESOURCES
journalArticle	Arayici, Yusuf; Aouad, Ghassan	Building information modelling (BIM) for construction lifecycle management	2010				
journalArticle	Wong, Kam-din; Fan, Qing	Building information modelling (BIM) for sustainable building design	2013				
journalArticle	Olawumi, Timothy O.; Chan, Danie	BUILDING INFORMATION MODELLING AND PROJECT INFORMATION MANAGEMENT FRAMEWORK FOR CONSTRUCTION PROJECTS	2019				
journalArticle	Kassem, Mohamad; Iqbal, Nahim; I	Building information modelling: protocols for collaborative design processes	2014				
journalArticle	Copeland, Samuel; Bilec, Melissa	Buildings as material banks using RFID and building information modeling in a circular economy	2020				
thesis	SANA, SHEHZADI	Circular Economy as a Cornerstone for material dependent Construction Industry.					
journalArticle	Leising, Eline; Quist, Jaco; Bocken,	Circular Economy in the building sector: Three cases and a collaboration tool	2018				EXTRA RESOURCES
journalArticle	KONUK, MERT; RESTORI, DAVIDE	Circular economy in the building sector: towards a holistic framework for implementing circular economy business models	2018				EXTRA RESOURCES
journalArticle	Benachio, Gabriel Luiz Fritz; Freitas	Circular economy in the construction industry: A systematic literature review	2020-07-01				
book	Høibye, Linda; Sand, Henrik	Circular economy in the Nordic construction sector: Identification and assessment of potential policy instruments that can accelerate a transition toward a c	2018				
journalArticle	Leising, E. J.	Circular Supply Chain Collaboration In the Built Environment	2016				EXTRA RESOURCES
conferencePaper	Van den Berg, Marc; Voordijk, Han	Circularity challenges and solutions in design projects: An action research approach	2019				
bookSection	Iyer-Raniga, Usha; Erasmus, Priyan	Circularity in the built environment: A focus on India	2020				
journalArticle	Budig, Michael; Heckmann, Oliver;	Computational screening-LCA tools for early design stages	2020				
journalArticle	Velenturf, Anne PM; Purnell, Phil; T	Co-producing a vision and approach for the transition towards a circular economy: perspectives from government partners	2018				
journalArticle	Hossain, Md Uzzal; Ng, S. Thomas	Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review	2018				
journalArticle	Honic, Meliha; Kovacic, Iva; Sibenil	Data-and stakeholder management framework for the implementation of BIM-based Material Passports	2019				
journalArticle	Ge, Xin Janet; Livesey, Peter; Wang	Deconstruction waste management through 3d reconstruction and bim: a case study	2017				
journalArticle	Zanni, Maria-Angeliki; Soetanto, Ro	Defining the sustainable building design process: methods for BIM execution planning in the UK	2014				
journalArticle	Akinade, Olugbenga; Oyedele, Luk	Design for deconstruction using a circular economy approach: barriers and strategies for improvement	2020				
journalArticle	Ryńska, Elżbieta D.	Design workshops and the circular economy	2020				
journalArticle	Fernando, T. P.; Wu, Kuo-Cheng; Ba	Designing a novel virtual collaborative environment to support collaboration in design review meetings	2013				
journalArticle	Ahuja, Ritu; Sawhney, Anil; Arif, M	Developing organizational capabilities to deliver lean and green project outcomes using BIM	2018				
journalArticle	Santos, Rúben; Costa, António Agu	Development of a BIM-based Environmental and Economic Life Cycle Assessment tool	2020				
journalArticle	Jayasinghe, Laddu Bhagya; Waldm	Development of a BIM-Based Web Tool as a Material and Component Bank for a Sustainable Construction Industry	2020				
journalArticle	Alhosni, Ibtisam Sulaiman; Amoudi	Drivers of adopting Circular Economy in Oman built environment	2019				
journalArticle	Gustafsson, Felicia	Embarking upon circular construction	2019				
journalArticle	Ibrahim, Rahinah; Abdul Ghafar, M	Embedding Work Culture in Building Information Modelling (BIM) for Enhancing Collaboration in Global Projects	2013				
journalArticle	Akinade, Olugbenga O.; Oyedele, L	Evaluation criteria for construction waste management tools: towards a holistic BIM framework	2016				EXTRA RESOURCES
journalArticle	Hjelseth, Eilif	Exchange of Relevant Information in BIM Objects Defined by the Role- and Life-Cycle Information Model	2010				
journalArticle	Nascimento, Daniel Luiz Mattos; Al	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context	2019				
journalArticle	Andersen, Mikkel Toppel; Findsen,	Exploring the benefits of structured information with the use of virtual design and construction principles in a BIM life-cycle approach	2019				
journalArticle	van den Brink, R.; Prins, M.; Straub	Finding the right incentives; circular business models for the construction industry	2017				
journalArticle	Palos, Salla; Kiviniemi, Arto; Kuusis	Future perspectives on product data management in building information modeling	2014				EXTRA RESOURCES
conferencePaper	Velasquez, C. Villamil; Salehi, N.; H	HOW CAN INFORMATION AND COMMUNICATIONS TECHNOLOGY SUPPORT THE LINK BETWEEN CIRCULAR ECONOMY AND PRODUCT LIFE CYCLE MANAGEI	2020				
journalArticle	Górecki, Jarosław; Núñez-Cacho, P	How to convince players in construction market? Strategies for effective implementation of circular economy in construction sector	2019				EXTRA RESOURCES
thesis	Gabro, Jemi	iBIM–integrated Building Information Modeling. An Integrated BIM Team in the Design Phase.	2014				
journalArticle	Chen, Qian; Hall, Daniel Mark; Ade	Identifying enablers for coordination across construction supply chain processes: a systematic literature review	2020				
journalArticle	Maskuriy, Raihan; Selamat, Ali; Ali,	Industry 4.0 for the construction industry—how ready is the industry?	2019				
book	BERTINO, GAETANO; MENCONI, FF	Innovative circular solutions and services for new buildings and refurbishments	2018				
journalArticle	GAETANO BERTINO; FRANCESCO N	INNOVATIVE CIRCULAR SOLUTIONS AND SERVICES FOR NEW BUILDINGS AND REFURBISHMENTS	2019				
conferencePaper	Jrade, Ahmad; Jalaei, Farzad	Integrating building information modelling with sustainability to design building projects at the conceptual stage	2013				
journalArticle	Akinade, Olugbenga O.; Oyedele, L	Integrating construction supply chains within a circular economy: An ANFIS-based waste analytics system (A-WAS)	2019				
journalArticle	Najjar, Mohammad; Figueiredo, Ka	Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building	2017				
journalArticle	Álvarez Antón, Laura	Integration of LCA and BIM considering early building/construction design stages	2013				EXTRA RESOURCES
journalArticle	Santos, Ruben; Costa, António Agu	Integration of LCA and LCC analysis within a BIM-based environment	2019				
thesis	Vik, Anders Lilleheim	Investigation of requirements for use of BIM-based LCA in early stages of building design	2018				
journalArticle	Bueno, Cristiane; Pereira, Lucas M	Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling	2018				
bookSection	Dalla Valle, Anna; Campioli, Andrea	Life Cycle BIM-Oriented Data Collection: A Framework for Supporting Practitioners	2020				EXTRA RESOURCES
journalArticle	Paik, Seong mok; Leviakangas, Pek	Making most of BIM in design: analysis of the importance of design coordination					
journalArticle	Chen, Jianguo; Su, Yangyue; Si, Hon	Managerial areas of construction and demolition waste: A scientometric review	2018				
journalArticle	Savolainen, Jussi	Managing Collaborative Design Processes in Construction Projects	2019				
journalArticle	Mostafa Khanzadi; Ali Kaveh; Moh	Optimization of Building Components with Sustainability Aspects in BIM Environment	2019				
journalArticle	Meyer, Charley	Optimizing the use of critical materials in the built environment using Building Information Modelling (BIM	2018				
journalArticle	Jin, Ruoyu; Yang, Tong; Piroozfar, F	Project-based pedagogy in interdisciplinary building design adopting BIM	2018				
journalArticle	Reizgevičius, Marius; Ustinovičius,	Promoting Sustainability through Investment in Building Information Modeling (BIM) Technologies: A Design Company Perspective	2018				
journalArticle	Alwan, Zaid; Greenwood, David; Gl	Rapid LEED evaluation performed with BIM based sustainability analysis on a virtual construction project	2015				
journalArticle	Häkkinen, Tarja; Kuittinen, Matti; F	Reducing embodied carbon during the design process of buildings	2015				
journalArticle	Cambier, Charlotte; Galle, Waldo; I	Research and Development Directions for Design Support Tools for Circular Building	2020				
journalArticle	Okakpu, Anthony; Ghaffarianhosei	Risk factors that influence adoption of Building Information Modelling (BIM) for refurbishment of complex building projects: stakeholders perceptions					
journalArticle	Nobre, Gustavo Cattelan; Tavares,	Scientific literature analysis on big data and internet of things applications on circular economy: a bibliometric study	2017				
journalArticle	Reychav, Iris; Maskil Leitan, Reuve	Sociocultural sustainability in green building information modeling	2017				
journalArticle	Kylili, Angeliki; Fokaides, Paris A.; S	Sustainability Tools for the Assessment of Construction Materials and Buildings	2016				
bookSection	Díaz, Joaquín; Antön, Laura Álvarez	Sustainable construction approach through integration of LCA and BIM tools	2014				
journalArticle	Margo Cole	Technical Excellence: Creating a circular economy	2014				
journalArticle	Ruiz, Luis Alberto López; Ramón, X	The circular economy in the construction and demolition waste sector–a review and an integrative model approach	2020				EXTRA RESOURCES
journalArticle	Lambrechts, Wim; Gelderman, Cee	The role of individual sustainability competences in eco-design building projects	2019				
thesis	SABRI, MAEN	The Use of Building Information Modelling (BIM) in Construction: An exploration of current challenges for collaborative construction	2018				
journalArticle	T. Bouazza; C. E. Udeaja; D. Greenw	The Use Of Building Information Modelling (BIM) In Managing Knowledge In Construction Project Delivery: A Conceptual Model	2015				
journalArticle	Solaimani, Sam; Sedighi, Mohamac	Toward a holistic view on lean sustainable construction: A literature review	2020				
journalArticle	Zanni, Maria Angeliki; Soetanto, Ro	Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements	2017				EXTRA RESOURCES
journalArticle	Munaro, Mayara Regina; Tavares, S	Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment	2020				
journalArticle	Petrova, Ekaterina; Pauwels, Pieter	Towards data-driven sustainable design: decision support based on knowledge discovery in disparate building data	2019				
journalArticle	Barbosa, Margarida Jerónimo; Pau	Towards increased BIM usage for existing building interventions	2016				
journalArticle	Iyer-Raniga, Usha	Using the ReSOLVE framework for circularity in the building and construction industry in emerging markets	2019-08				
journalArticle	Grilo, António; Jardim-Goncalves, I	Value proposition on interoperability of BIM and collaborative working environments	2010				
journalArticle	Abrishami, Sepehr; Goulding, Jack;	Virtual generative BIM workspace for maximising AEC conceptual design innovation	2015				

A.2 2nd Literature Screening

Item Type	Author	Title	Date	Decision
conferencePaper	Di Biccari, C.; Abualdenien, J.; Borrmann, A.; Corallo, A.	A BIM-based framework to visually evaluate Circularity and Life Cycle Cost of buildings.	2019	
journalArticle	Osobajo, Oluyomi A.; Oke, Adekunle; Omotayo, Temitope; Ob	A systematic review of circular economy research in the construction industry	2020	
journalArticle	Jalaei, Farzad; Jalaei, Farnaz; Mohammadi, Sepehr	An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects	2020	
journalArticle	Mohammed, Abdullah Badawy	Applying BIM to achieve sustainability throughout a building life cycle towards a sustainable BIM model	2019	
journalArticle	Aguiar, A.; Vonk, R.; Kamp, F.	BIM and Circular Design	2019	
journalArticle	Delgado, Juan Manuel Davila; Oyedele, Lukumon O.	BIM data model requirements for asset monitoring and the circular economy	2020	
journalArticle	Wu, Wei; Issa, Raja RA	BIM execution planning in green building projects: LEED as a use case	2015	
journalArticle	Akbarieh, Arghavan; Jayasinghe, Laddu Bhagya; Waldmann, D	BIM-Based End-of-Lifecycle Decision Making and Digital Deconstruction: Literature Review	2020	
journalArticle	Santos, Rúben; Costa, António Aguiar; Silvestre, José D.; Vand	BIM-based life cycle assessment and life cycle costing of an office building in Western Europe	2020	
journalArticle	Eberhardt, Leonora Charlotte Malabi; Birkved, Morten; Birgisc	Building design and construction strategies for a circular economy	2020	
journalArticle	Copeland, Samuel; Bilec, Melissa	Buildings as material banks using RFID and building information modeling in a circular economy	2020	
journalArticle	Benachio, Gabriel Luiz Fritz; Freitas, Maria do Carmo Duarte; T	Circular economy in the construction industry: A systematic literature review	2020-07-01	
book	Høibye, Linda; Sand, Henrik	Circular economy in the Nordic construction sector: Identification and assessment of potential policy instruments that can accelerate a trai	2018	
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