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Open Data Platform for Buildings' Circularity assessment at early design stage

Master Thesis
MSc in Construction Management and Building Informatics

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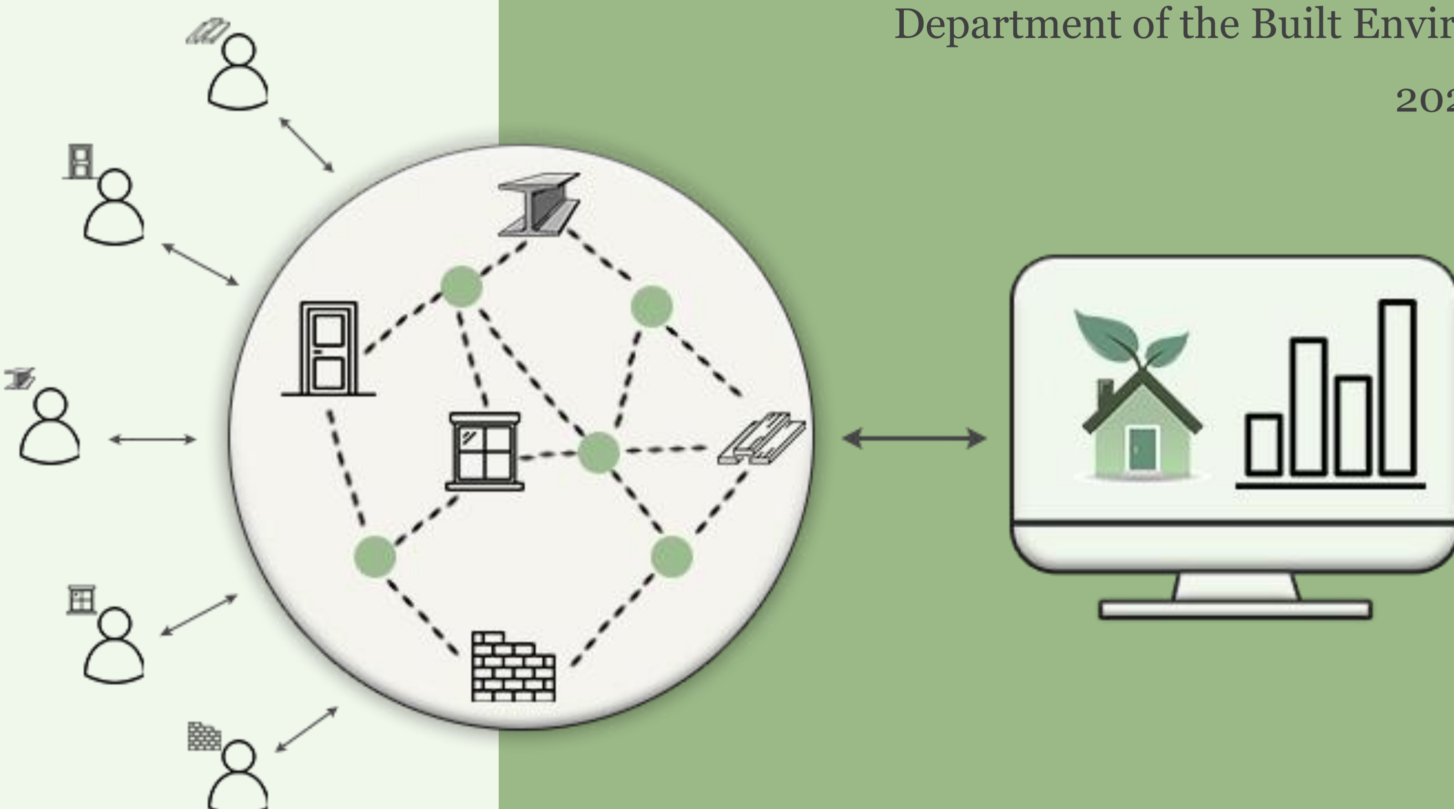

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Title:	**Open data platform for buildings' circularity assessment at early design stage**
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“There is only one planet Earth, yet by 2050, the world will be consuming as if there were three”

- (European Commission, 2020b)

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Abstract

Environmental issues and the damage industries have caused to the nature are undeniable at the present time. Unfortunately, construction industry is found to be the top polluter and the largest consumer of the natural resources. The currently used linear economy model at the end of the products' life converts these resources into waste and encourages further resource consumption. Nevertheless, there is a better approach. Circular Economy model is advocated to help industries to perform in environmentally friendly manner and eliminate the waste. However, currently not many CE implementations can be seen in the built environment and it is acknowledged, that there are many factors influencing such condition. Even So, this study focuses on the technical instruments deficiency in order to move towards the more circular buildings. Many scholars agree that the early design phase is the best time to evaluate the decisions made for the future building, as at this time changes can be done with the least effort and lowest costs. Though, at the moment designers are not equipped with the necessary tools to carry out the assessment. Therefore, this study investigates the currently existing assessment tools, models, strategies as well as the possibilities to retrieve required data for the circularity assessment. According to the findings, a novel assessment framework is proposed while taking advantage of the Semantic Web and Linked Open Data technologies to provide a structure and openly available platform for a much-needed product circularity data database. Furthermore, the proof of concept is demonstrated as a first prototype of a new BCAO ontology dedicated to assist structuring the heterogeneous and scattered manufacturer products' data for the circularity assessment.

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Acknowledgements

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Reader's Manual

The reader's manual is proposed in order to give an overview of the report anatomy and guide the reader between the sections. *Figure I* represents the structure of the report which is divided in four sections indicated by grey dashed line. The first section is dedicated to introducing the purpose of the study. Here the problem formulation is stated together with the following research sub-questions. A research design is presented with the aim of defining the study and proposing the methodology. Finally, before starting the desk research the main concepts and definitions are given.

The desk research is necessary in order to identify all the latest and relevant contributions to answer the problem formulation and sub-questions. It is divided in three chapters according to the main topics of the research content. Subsequently, desk research analysis is done, and the identified gaps listed.

The third section of the report employs the results of the desk research and combines them with the outcomes of the interviews with industry professionals in order to confirm the desk research results, derive the requirements for the system and propose a conceptual circularity assessment system framework. The section is divided accordingly including the assessment analysis, ontology analysis and new ontology conceptual definition.

Finally, in section four the first prototype is developed and validated, leading to the final report chapters namely the discussion, limitations, conclusion, and future work.

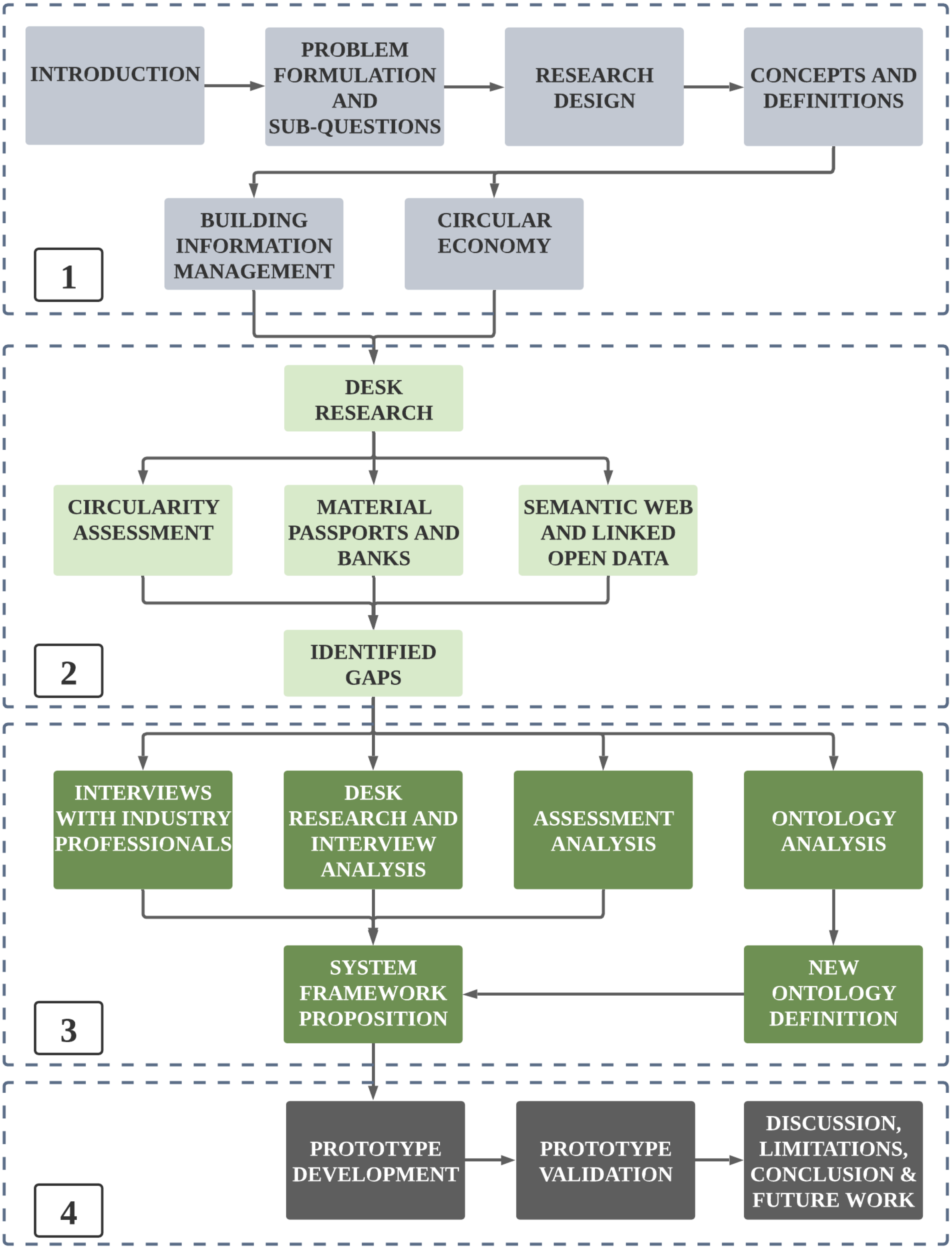

Figure I. Research structure.

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List of Abbreviations

Abbreviation	Definition
ABox	Assertion Box
ACM	Association for Computing Machinery
AEC	Architecture, Engineering, and Construction
AIA	American Institute of Architects
API	Application-Programming Interface
APP	Application
BAMB	Buildings as Material Bank
BCAO	Building Circularity Assessment Ontology
BCF	BIM Collaboration Format
BCI	Building Circularity Indicator
BE	built Environment
BFO	Basic Formal Ontology
BIM	Building Information Management/Modelling
BIMMO	BIM Manufacturer Ontology
BIMSO	BIM Shared Ontology
BMP	Building Material Passport
BO	Building One
BOM	Bill of Materials
BOT	Building Topology Ontology
BPO	Building Product Ontology
BREEM	Building Research Establishment Environmental Assessment Method
bSDD	Building SMART Data Dictionaries
BSI	Building SMART International
BWPE	BIM Based Whole Life Performance Estimator
C2C	Cradle to Cradle
CAD	Computer-Aided Design
CAMO	Circular Activities and Materials Ontology
CB’23	Circulair Bouwen
CE	Circular Economy
CEO	Circular Exchange Ontology
CI	Circularity Indicator
CIBSE	The Chartered Institution of Building Services Engineers
CLT	Cross Laminated Timber
CQs	Competency Questions
BIM-DAS	Building Information Modelling based Deconstructability Assessment Score
DBMS	Database Management System
DFD	Design for Disassembly
DFM	Design for Manufacturing
DFX	Design for (X) or Design for Excellence
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DICBM	Digital Construction Building Materials
EC	European Commission
EC	Embodied carbon
EE	Embodied energy
EMF	Ellen MacArthur Foundation

EOL	End-of-Life
EPD	Environmental Product Declaration
EU	European Union
FGMO	Functionally Graded Materials
FIF	Federated Interoperability Framework
FOL	First-Order-Logic
FRS	final Retention in Society
GIS	Geographic Information System
GUID	Globally Unique Identifier
GWP	Global Warming Potential
HVAC	heating, Ventilation, and Air Conditioning
IAI	International Alliance for Interoperability
IASDOP	Integrated Approach for the Sustainable Design of Products
ICE	Inventory of Carbon and Energy
ID	Identifier
IDM	Information Delivery Manual
IFC	Industry Foundation Classes
OWL	Web Ontology Language
IFD	International Framework for Dictionaries
IRI	Internationalized Resource Identifiers
ISO	International Organization for Standardization
JSON	JavaScript Object Notation
KPI	Key Performance Indicators
LBD	Linked Building Data
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
LFI	Linear Flow Index
LOD	Level of Development/Detail
LOD	Linked Open Data
LOT	Linked Open Terms
LOV	Linked Open Vocabularies
LUPO	Lightweight Upper Ontology
MASON	Manufacturing Semantics Ontology
MATONTO	Materials Ontology
MCCO	Manufacturing Core Concepts Ontology
MCI	Material Circularity Indicator
MDSE	Material Data via Semantic Information Extraction
MP	Material Passports
MSDL	Manufacturing Service Description Language
MSDS	Material Safety Datasheets
MVC	Model, view, controller
MVD	Model View Definitions
NIBS	National Institute of Building Science
OE	Ontology Engineering
ONTO-PDM	Product-driven Ontology for Product Data Management
OPM	Ontology for Property Management
ORSD	Ontology Requirement Specification Document

P-PSO	Politecnico di Milano production systems ontology
PAS	Publicly Available Specifications
PBCI	predictive Building Circularity Indicator
PCI	Product Circularity Indicator
PMPO	Part-Focused Manufacturing Process Ontology
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
Pset	Property Set
R2RML	Relational Database to Resource Description Framework Mapping Language
RBox	Rule Box
RDF	Resource Description Framework
RIF	Rule Interchange Format
SCI	System Circularity Indicator
SEF	Systems Engineering Fundamentals
SM	Semantic Web
SPARQL	Simple Protocol and RDF Query Language
SPF	STEP Physical File
SQ	Sub-question
TBox	Terminology Box
UI	User Interface
UOR	In-Use Occupation Ratio
W3C	World Wide Web Consortium
XML	Extensible Markup Language
XSD	XML Schema Definition
YSTAFDB	Yale Stocks and Flows Database

1. Introduction

"There is only one planet Earth, yet by 2050, the world will be consuming as if there were three" (European Commission, 2020b, p. 2). The current linear economy paradigm is based on the "take-make-use-dispose" model. Maintaining such approach will exhaust the natural resources and lead to their depletion (Cottafava & Ritzen, 2020). The European Commission latest action plan enunciate that 90% of biodiversity loss is due to the global consumption of natural resources, which is estimated to double over the next forty years accompanied by 70% increase in waste generation. The built environment is deemed as a significant contributor to resources and energy consumption, as well as to waste generation (Benachio et al., 2020; Cottafava & Ritzen, 2020; Heisel & Rau-Oberhuber, 2020; Pomponi & Moncaster, 2017). On top of that, it is responsible for 50% of the global material extraction, whereas the construction industry is accounted for 35% of the waste generated in the European region alone (European Commission, 2020b).

These significant environmental burdens increased the demand for innovative approaches (Geng et al., 2012). Circular economy (CE) concept is receiving a great deal of attention and induces big hopes for overcoming the linear economic detrimental impact on the environment. Additionally, CE concepts are recommended to be implemented to achieve a sustainable development (Saidani et al., 2019). CE sustainable model seeks to separate the economic growth from exploitation of natural resources through reduction of raw material extraction and maintaining the already used resources in circulation (Benachio et al., 2020; Corona et al., 2019). As for the built environment this transition from linear to circular model is considered fundamental in relation with reducing the pressure on the natural resources as well as increasing profitability and job creation (Linder et al., 2017; Pomponi & Moncaster, 2017). It is estimated that CE has the potential to rise the European Gross Domestic Product (GDP) by 0.5% providing around 700,000 new jobs by 2030 (European Commission, 2020b).

However, fundamental differences between the linear and circular models, requires the ability to measure the performance of CE towards this transition (European Academies Science Advisory Council (EASAC), 2016). Therefore, various CE indicators were developed to support practitioners and decision makers to embrace the CE practices, monitor its adoption and performance towards sustainable development (Corona et al., 2019; Geng et al., 2012; Saidani et al., 2019). In light of that, different proposals with the aim of supporting the adoption of CE model were commenced. For instance, Ellen MacArthur foundation is a well-known initiative addressing the biological and technical cycles of product and material nutrients (EMF, 2013). Similarly, the Material Circularity Indicator (MCI) is the broadest used indicator to measure how well a product or company performs in the context of CE (EMF & Granta Design, 2015). Moreover, CE indicators can play a major role in the transition of the built environment, more specifically the construction industry towards the CE compliant approaches. The aim of this transition is to maintain the value of the materials and products used in construction, by reutilizing them at their end of life (EOL). Consequently, circular buildings have gained increased attention for the contribution to a smooth CE transition with consideration to EOL (Akbarieh et al., 2020). Adopting circular building design strategies such as design for disassembly (DFD) (Durmisevic Elma, 2006), design for adaptability (Schmidt et al., 2010) or design for material recovery (EMF & Granta Design, 2015), can enhance the construction industry impact on the environment and promote the circularity of materials and products in closed loops (Kanters, 2020).

The assessment of building's circularity will enable practitioners (architects, engineers, designers, etc.) to quantify their progress towards a sustainable development (Saidani et al., 2019). Such practice of introducing the CE concepts should be implemented at early phase of a project (Benachio et al., 2020). Subsequently, transparent, and reliable CE related data is significant to provide the necessary input for a successful assessment implementation (Akbarieh et al., 2020). However, the fragmented nature of construction supply chain hinders CE data exchange (Adams et al., 2017). This need for CE related information led the creation of the building's material passport concept. This concept can enable data documentation and collection for different building's materials and products which can support the circularity assessment while ensuring an effective collaboration between different stakeholders (Benachio et al., 2020; Luscuere, 2017; Munaro et al., 2019). In addition, Building Information Modelling (BIM) as a process can play a key role in the data exchange by increasing information management quality (Ozturk, 2020). A BIM model can perform as a database, storing information required during the project life cycle (Ghaffarianhoseini et al., 2017). In relation to circular buildings, the integration of BIM into the assessment process would enhance the interoperability and provide accurate and reliable project data (Cambier et al., 2020). However, concerns with respect to the ownership and accuracy of the stored data may arise, especially when dealing with large datasets (Sacks et al., 2018). Nonetheless, advancement in technologies can address issues related to the management of large amounts of CE related data (Pomponi & Moncaster, 2017). Linked Open Data (LOD) technologies can improve the accessibility and retrieval of such specific information (Kebede et al., 2020). Therefore, enhancing the current practices of structuring and storing the data as well as utilizing a common vocabulary to define and retrieve the necessary information is vital for the effective assessment (Pauwels et al., 2017).

Problem formulation

The initial literature review provided insights into the current industry situation of exercising the linear economy model which follows the "take-make-use-dispose" approach and its consequences on the environment. CE concept is seen as a potential solution to ameliorate the traditional linear economy practices. In addition, the transition of the built environment to a circular model would bring many benefits particularly to the construction sector. Therefore, the concept of circular building gained increased attention aiming for materials and products of the building elements to be reutilized at their EOL. In order to help practitioners and decision makers to quantify the progress of transition towards the circular model, different indicators and assessment models have been developed. In the built environment such indicators could be utilized to assess the level of buildings circularity, especially at early stage of the design. To perform the building's circularity assessment various requirements have been derived from the initial literature review which can be depicted in Figure 1. Three inputs are important to be addressed in order to achieve the desired output. First, the assessment criteria need to be determined in order to identify the approach of conducting the assessment. Second, an early design model should be ready containing all the required inputs for the assessment from the designer side. Third, the data about manufacturer products should be provided and sufficient to assess the design according to the selected assessment model.

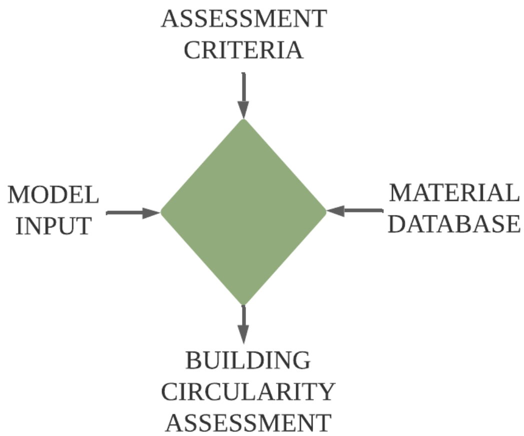


Figure 1: Diamond model of Building Circularity assessment

Based on the initial literature review and the identified inputs required to perform the assessment, the aim of this research is to provide a system framework illustrating how the circularity assessment can be carried out at early design phase. Therefore, the main question of this research can be formulated as:

How can Linked Open Data technologies be utilized for buildings' circularity assessment at early design stage to guide design decisions towards circular building?

In addition, four supplementary sub-questions need to be addressed in order to answer the main problem formulation:

1. What criteria is necessary to assess and what are the existing assessment practices/models?
2. What are existing practices for structuring and storing material/product information necessary for assessment?
3. How can Linked open Data technologies aid for structuring and storing necessary data for circularity assessment?
4. How the proposed solution will guide design decisions towards circular building?

Delimitation

Regarding the time limitations this study is focused on the technical side of circularity assessment realization, without taking into consideration the legislative, managerial, economic, or other factors important to CE implementation in AEC industry.

2. Research Design and methods

In this chapter the theoretical considerations and research strategy is presented, leading to the creation of a research design. The suggested research design is divided in three phases, therefore each of them is explained while at the same time addressing the research validity and researchers' bias concerns. Further, all the methods applied in the study are listed and described in reflection to the context.

2.1. Theoretical considerations and research strategy

Initial literature review has grounded the foundation towards the main problem formulation and following sub-questions. Nevertheless, to answer all these questions in a systematic manner and provide valid results an appropriate research strategy must be selected. Johnson & Christiansen, (2014) distinguishes two major scientific methods to conduct a research, namely exploratory and confirmatory. The purpose of exploratory method is to discover a theory by gathering relevant data and generalizing, while confirmatory method focusses on testing an existing theory. As the goal of this thesis is to identify existing contributions from the scholars and industry relevant to the early design buildings' circularity assessment leading to a proposition for a novel approach, research is exploratory by nature.

The next step is to define a research paradigm. According to Johnson & Christiansen (2014) there are three major research paradigms: qualitative, quantitative, and mixed research. The main difference between them is the type of data collection the research relies on. Therefore, quantitative study relies on quantitative data collection, qualitative on qualitative data collection and mixed method is a combination of both. It was distinguished earlier that the research itself is exploratory, thus collecting only quantitative data would not answer the problem formulation. Though quantitative data could help to back up some generalizations about the current situation in the industry related to implementation of circular economy, it is not the main goal for this research and considering the time limitations was decided to rely purely on qualitative data collection.

As was mentioned before qualitative study follows the inductive approach, meaning that generalizations are made based on data collected. In order to fully answer the problem formulation and following sub-questions this thesis research process was divided in three phases (Figure 2). The first phase builds on desk research which includes data collection from previous researchers, relevant foundations, legal documentations, or industry practices available online followed by data analysis. The second phase is instrument creation. During this phase, the information collected in phase one is combined with new findings gathered from potential instrument users to propose a system framework and first prototype. Finally phase three is necessary for suggested solution validation which will lead towards drawing the final conclusions.

2.2. Research design

Research design is commonly described as a plan or strategy for carrying out a research in order to achieve the best results and validate them while avoiding the bias. *"The function of a research design is to ensure that evidence obtained enables us to answer the initial question as unambiguously as possible"* (De Vaus, 2001, p. 9). By all means research design should be unique and tailored specifically for each project. Considering this thesis research was divided in four major stages namely data collection, data processing, instrument creation and application validation. Each of the three research phases described previously contains one or more research stages. Phase one includes the introduction, problem formulation, data collection and data analysis. Phase two concerns about the instrument creation stage. Phase three consists of application validation stage accompanied by drawing final conclusions while exploring the limitations, proposing the future work, answering the research questions, and identifying the contribution of this study. To achieve the best results specific methods are proposed for each of the stages. The research itself is divided according to the sub-questions drawn out from the main problem formulation. The first two sub-questions are driving the phase one and are answered during the data collection and data processing stages. Sub-question three starts the phase two where the instrument system framework is created and the first prototype for circularity assessment is proposed. Finally, answering the sub-question four during phase three will ensure the application validation and lead the study to the final conclusions. The visual representation of the research design can be seen in Figure 2.

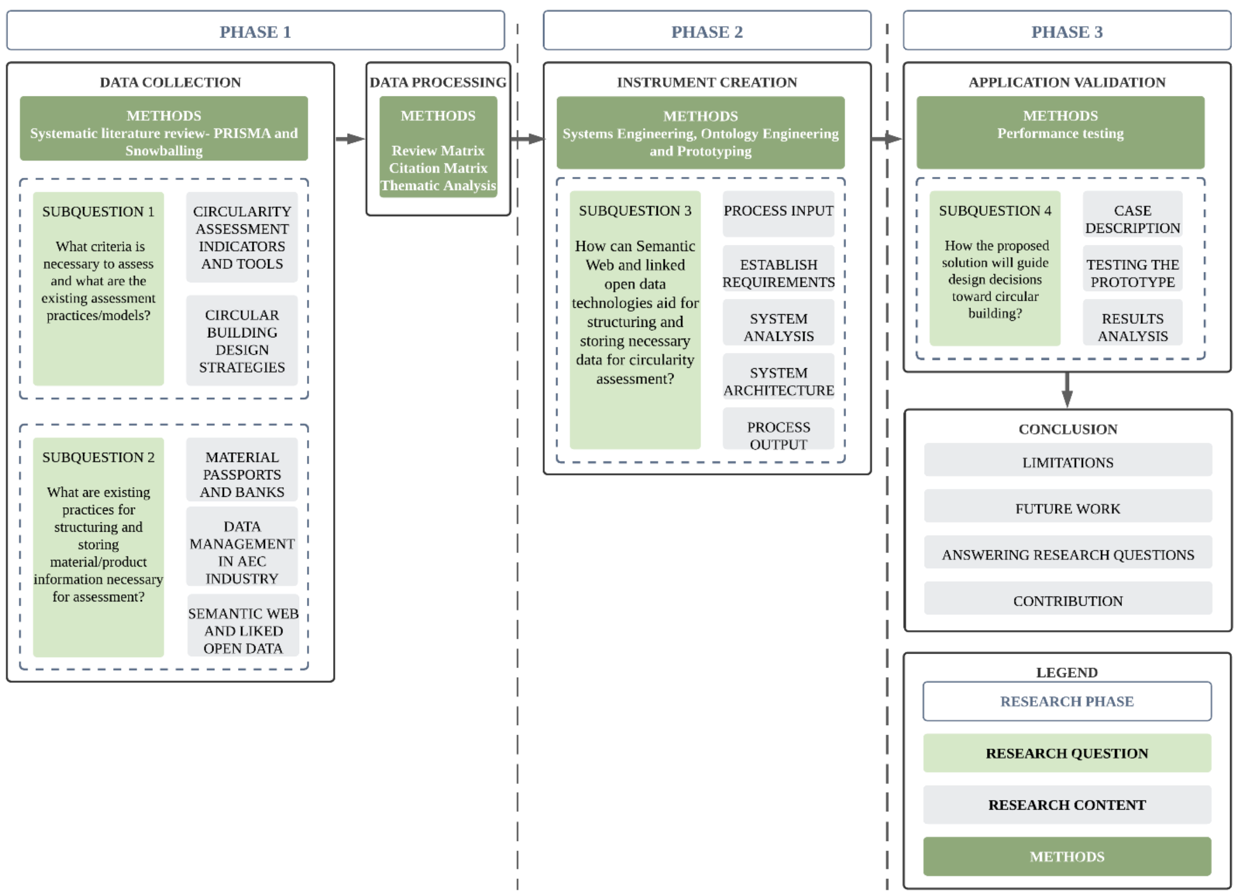


Figure 2: Research design

2.2.1. Phase one: Data collection and Processing

Initial literature review on Circular Economy in the AEC industry led to the realization that the biggest influence towards a circular building can be done during the early design stage when changes can be performed requiring the least effort and funds. Ergo that raised a question how the early design could be assessed for circularity and what are the current practices. Having that in mind a diamond model for main assessment pillars was drawn showing the primary inputs needed (Figure 1 in *"1. Introduction"*). This model later was expanded as a mind map branching out each of the inputs and revealing the core areas for this research. Consequently, a final problem formulation was drawn, and related research areas identified from the mind map, later covered in the sub-questions.

This early analysis laid the foundation for structuring the data collection stage. As it is seen in Figure 3 the data collection stage is divided in two big clusters dedicated to answer the first two research sub-questions indicated by the green color. Grey rectangles circled by the dashed line together with the sub-questions shows the main topics to be covered in that area which is further broken down into related sub-topics led by the arrows. In order to reach the depth of these topics and identify relevant clusters PRISMA framework (Liberati et al., 2009) and snowballing (Wohlin, 2014) was chosen as the desk research methods.

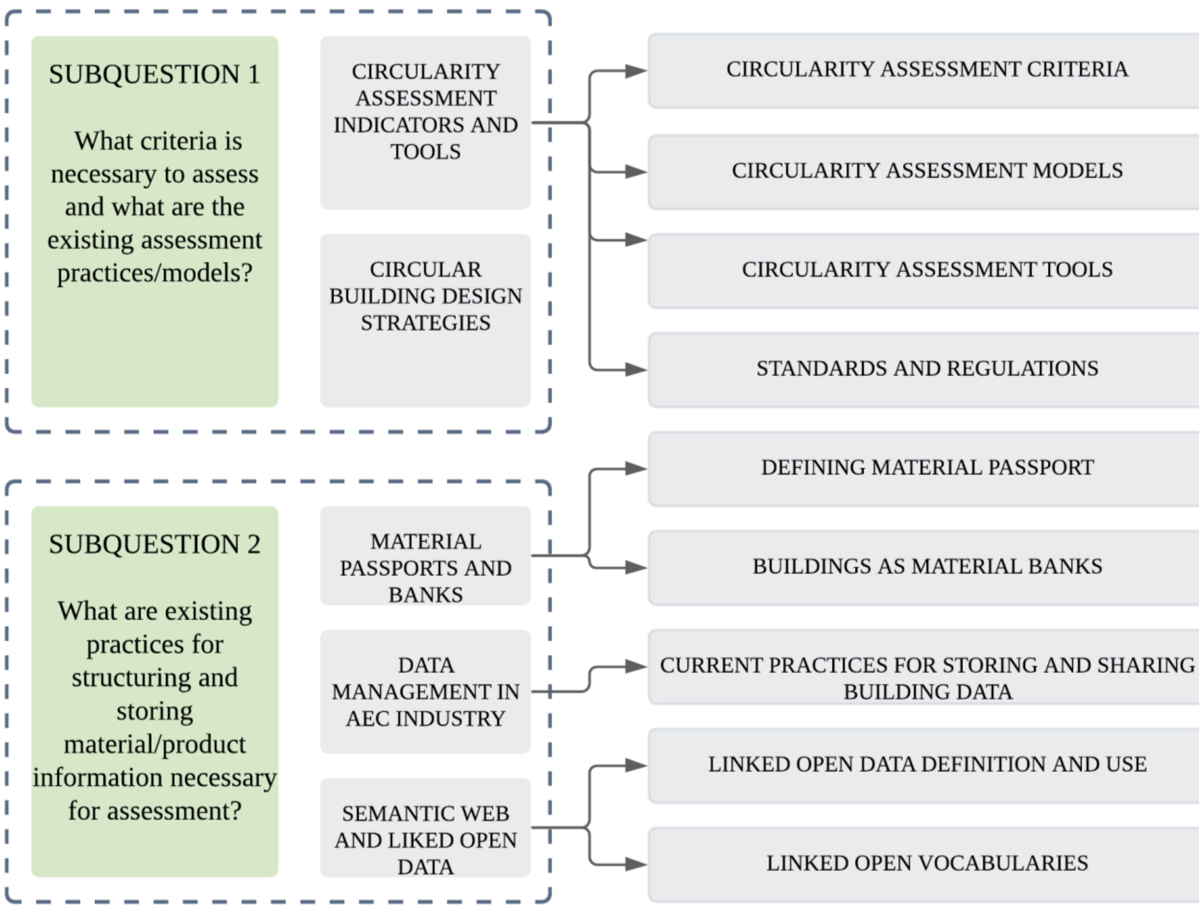


Figure 3: Data collection stage breakdown

During the data processing stage all the collected data must be synthesized. Johnson & Christiansen (2014) defines data synthesis as the selection, organization and analysis of the materials collected. To ensure the validity of research and avoid the bias as much as possible a combination of methods is used in order to synthesize the data. Firstly, a *Snowballing* protocol is made to keep track of keywords, search strings and databases used as well as to define inclusion or exclusion criteria. Literature review matrix is used for keeping the records of selected materials while *Snowballing* tracking table helps to keep track of included and excluded papers during the iterations. At the same time PRISMA framework checklist and flow diagrams are utilized which are aimed at transparent reporting of systematic review (Liberati et al., 2009). Thematic analysis is used to structure the literature review outcomes a well as numerous tables are employed in order to represent the main outcomes of research sections.

2.2.2. Phase two: Instrument Creation

Answering the first two sub-questions in phase one allows the research to move forward and begin the phase two. This phase is dedicated for instrument creation stage, meaning that all data gathered and synthesized during phase one is now going to be utilized for making the decisions leading to the creation of instrument system framework and first prototype. Of course, during this stage, it is important to remember the industry and potential users who is going to benefit from the tool. Thus, to gather all the requirements and proceed with instrument development in a systematic manner *Systems Engineering Fundamentals* (SEF) (Lightsey, 2001) guidelines are utilized. In reflection to this thesis and considering the time limitations, it is important to mention that the authors are not trying to develop a fully functioning and integrated system. In contrary, the goal for this project is to identify the latest contributions, best practices and industry needs to make the first steps bridging the gap towards the circular building. Therefore, only the relevant parts of *Systems Engineering Fundamentals* will be applied.

Systems Engineering

According to (Lightsey, 2001) systems engineering consists of two parts namely the technical domain where the systems engineer operates and systems engineering management. Regarding the scope of this project only a part of systems engineering management guidelines will be implemented which are necessary to propose a valid system framework and develop the first prototype. Systems engineering management itself consists of three interconnected parts: development phasing, systems engineering process and life cycle integration. Development phasing consists of three levels namely concept level, system level and subsystem/component level. At the end of concept level, a system concept description should be ready. System level translates the concept into system in form of performance requirements terms and following subsystem/component levels produces sets of subsystems and components descriptions, detailed descriptions, or characteristics. Systems engineering process is an iterative technique which is employed during all levels of development phasing. It is used for transforming the needs and requirements into system descriptions, generating information for decision makers, and providing input for the next level of development. Life cycle integration concerns about all life cycle needs during the development process and involves eight primary life cycle functions: disposal, training, verification, operation, support, development, deployment, and manufacturing/ production /construction.

Considering SEF (Lightsey, 2001) guidelines phase two- instrument creation, was structured following five subsequential steps: process input, establishment of requirements, system analysis, creation of system framework and process output namely the prototype. Regarding this thesis process input is divided in two main sources: desk research output from phase one and potential user input. Potential user input is retrieved during interviews with industry professionals which are picked for intentional sampling. During the next step data gathered from interviews is synthesized and compared with the information retrieved during the desk research. Requirements are established considering the process inputs analysis and final system framework is proposed. Prototyping is introduced as a method for the process output step. As it was mention before fully functioning system is not the goal of this thesis, therefore the output of the first prototype is considered as a process output, for first development phase.

2.2.3. Phase three: Application validation and Conclusion

At the end of phase two the third sub-question is answered therefore phase three is dedicated to answer the last sub-question and make conclusions exposing the limitations of solution, proposing following future work, and indicating the contribution. In order to answer the fourth sub-question performance testing as a case study method is introduced which consists of three steps: case description, testing the prototype and results analysis.

2.3. Validity

Validity is a common point for discussion of any research. According to Johnson & Christiansen (2014) the term *validity* was mostly attached to quantitative studies, as it was always difficult to establish measures to validate qualitative studies. Some researchers even pushed to the extreme saying that this term is not relevant to qualitative study. Nevertheless, authors disagree saying that qualitative research validity should be addressed by checking if it is plausible, credible, trustworthy and defensible. Guba et al. (1979) refer to the same issue related to validity of qualitative research and lays the foundation for qualitative study evaluative criteria namely credibility, transferability, dependability and confirmability. Trochim (2020) compares these criteria to quantitative study evaluation criteria respectively internal validity, external validity, reliability, and objectivity. In reflection to this qualitative study criteria can be grouped into internal and external validity (Figure 4).

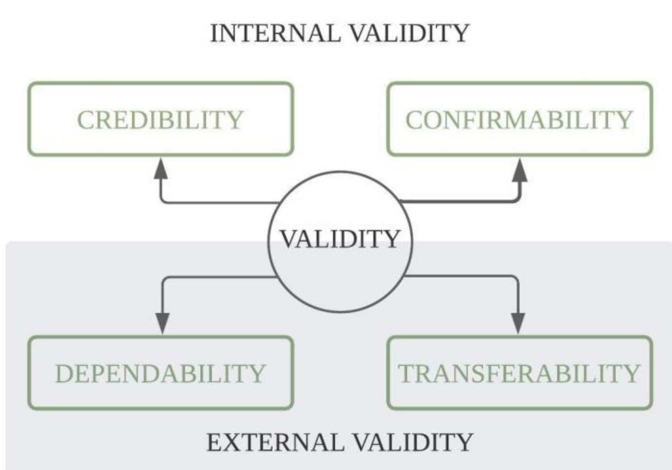


Figure 4: Qualitative study validity evaluative criteria

Internal validity addresses human factors of researchers and participants including credibility and confirmability criteria. Credibility is often named as the most important factor and could be portrayed as the confidence in the 'truth' of the findings (*Lincoln and Guba's Evaluative Criteria*, 1985). There are multiple methods to check the credibility of the research involving the most popular method called *triangulation*, but it is only the readers/participants who can really judge the credibility of research. Johnson & Christiansen (2014) defines *triangulation* as a validation approach using multiple investigators, methods, data sources, and/or theoretical perspectives in the search for convergence of results. Confirmability on the other hand is deeply rooted in the researcher's bias, motivation, or interest. There are as well some methods proposed to keep the researchers on track regarding the confirmability criteria. For example, Johnson et al. (2014) names methods like *reflexivity*, referring to the self-reflection and awareness of own bias, or *negative-case sampling*, which push the researcher into finding evidence to disconfirm his or her expectations or generalizations. Triangulation can be as well used to assess the confirmability.

External validity concerns about generalizations of findings. External validity includes dependability and transferability criteria. Dependability means that the research can be replicated or repeated and the findings are consistent, where transferability shows that the findings are reusable and can be adopted in other contexts (Lincoln and Guba's Evaluative Criteria, 1985). According to Johnson & Christiansen (2014) generalizability is not the purpose of qualitative study, therefore it is considered as a weakness of qualitative research. Of course, there are some methods like *external audits* to assess the external validity of the research, but even the method itself holds some drawbacks and it is not that commonly practiced.

By this brief review of qualitative study validity, the authors intent is to show the reader that research group is aware of ambiguity lying in the qualitative study validity evaluation. There are multiple qualitative study validation strategies proposed by Johnson & Christiansen (2014). The authors decided to apply few of the proposed strategies, considering the scope and time limitations for this project. A critical friend strategy fits well as the research is done by two group members; therefore, the work is constantly reviewed by each other. Multiple data sources are used to get deeper understanding of the problem; desk research is based on both peer-reviewed journals articles or conferences papers and on grey literature; interviews are based on intentional sampling trying to reach for a diversity of stakeholders and viewpoints. As this research is a university thesis project, it is done under a close supervision of university professors, therefore multiple investigators strategy can also be applied. Furthermore, the project is divided in three phases, each of the phase encompass various methods which also works as a strategy to validate the research. Participant feedback or member checking strategy is a big part of systems engineering field and is a crucial element for phases two and three.

Researcher Bias

Researcher's bias is unavoidable during qualitative study as all the data collected must be interpreted in some way. Still, it is important to be aware of your own bias so the study can be as unambiguous as possible. Methods as self-reflection and intentional contradictive information seeking can help to reduce the risk of researcher bias.

Finally, the authors are also aware of the external biases carried by the research participants. Therefore, desk research is targeted to various sources and databases, while the interviews are prepared with open ended questions and structured to avoid suggestive voice. Intentional sampling is used to reach the variety of stakeholders.

2.4. Methods

A variety of methods are used during the research in order to reach the best results, validate them and draw final conclusions. In this sub-chapter a short description of the utilized methods and their reflection to the research context is provided.

2.4.1. Systematic Literature Review

Prisma

PRISMA is a framework dedicated for a transparent reporting of a systematic review (Liberati et al., 2009). The method is combined of evidence-based minimum set of templates: PRISMA check list and PRISMA flow diagram. The checklist is divided in seven sections which are further broken down in multiple topics with corresponding checklist item. The purpose of the checklist is to guide the researcher towards critical analysis of selected studies.

To select the relevant studies PRISMA flow diagram is proposed. The diagram is divided in four stages: identification, screening, eligibility and included studies. During the identification stage relevant databases for research are chosen and predefined search queries are typed in. In this study *Web of Science* and *SCOPUS* were chosen as examined databases as they cover multidisciplinary fields and provide useful features to refine the search (Kebede et al., 2020). The search queries for relevant research concepts are stated in a tabular representation in the beginning of each literature review of related works subchapter. Further, following the PRISMA flow diagram, the duplicates found between two databases are excluded so the screening stage can begin. During the screening, the unique studies are assessed based on the title and later based on the abstract. Lastly, chosen studies are evaluated by full text for eligibility and final number of included studies for qualitative synthesis are stated. The flow diagram was complimented with snowballing of the last set of identified papers. Research findings are documented in literature review matrix.

Snowballing

Snowballing is a method for systematic literature review providing guidelines designed for a productive and problem focused research (Wohlin, 2014). In this research snowballing is used as a complimentary study based on *Google Scholar* database separately for each big topic answering the problem formulation sub-questions one and two. Before starting the snowballing procedure, a snowballing protocol is made indicating the keywords, search strings, synonyms, databases as well as inclusion and exclusion criteria for each investigated topic.

Literature review matrix is used to document all the findings including reference information, research design and subject characteristics, data collection methods and main discoveries. As snowballing method is based on reference and citation tracking called backward and forward snowballing, it is important to keep track of the papers included for different iterations as well as the number of papers included or excluded during the process. To achieve that a snowballing tracking matrix is made. Citation matrix helps to keep track of authors referring to each other or citing each other’s work, which allows to identify researchers’ clusters and make sure that authors are not locked in one cluster. Finally, to synthesize the collected data a thematic analysis is used, meaning that the research results are presented to the reader distributed by topic, while as well implementing tabular data representation to showcase the findings in a constructive manner.

2.4.2. Interviews

During the phase two individual semi-formal interviews with industry professionals are conducted based on intentional or non-random sampling. Questionnaires are constructed built on guidelines presented by Johnson & Christiansen (2014) and are drawn from information found during the desk research. Interview participants are kept anonymous in order to create a safe atmosphere for sharing their personal experiences, thoughts, and ideas. To avoid researcher's bias questions are reviewed not to be suggestive and made with an open-end creating the space for discussion. The goal of the interviews is to find out about the current company practices regarding circular economy, technical settings, data storage and sharing practices. To analyze the results framework method is implemented following seven steps: gathering transcriptions, familiarizing with the interviews, coding, developing analytical framework, applying analytical framework, charting the data into framework matrix and data interpretation (Gale et al., 2013). The interview findings are used in phase two in order to establish the requirements for system framework creation and prototype development.

2.4.3. Ontology Engineering

Ontology engineering (OE) is a complex process, which according to LOT methodology (María Poveda Villalón et al., 2019) is combined from four iterative activities: requirements specification, implementation, publication and maintenance (Figure 5). LOT was built on top of commonly used NeOn methodology for ontological engineering activities (Espinoza-Arias et al., 2020). While NeOn methodology (Suárez-Figueroa et al., 2012) provides in depth explanation for nine scenarios for collaboratively building ontologies and networks, glossary of processes and activities as well as a collection of ontology life cycle models, LOT process model gives a more concentrated overview.

All main activities of LOT methodology include ontology developers, users, and experts. Users are especially emphasized during the ontology development and should be involved in all key processes (Elisa F. & Deborah L., 2019). They are particularly important during the first activity-ontology requirement specification. The goal of this phase is to state why ontology is being built, which are the intended users, who are the end users, and what specific requirements ontology should fulfil (Suárez-Figueroa et al., 2012). Competency questions technique proposed by Grüninger & Fox (1995) are often used to guide the requirement specification process. According to Suárez-Figueroa et al. (2012) ontology requirements can be classified in functional (content specific requirements for particular knowledge and terminology represented by ontology) and non-functional (refer to characteristics, qualities, or general aspects not related to the ontology representing content). An outcome of the first LOT main activity is *Ontology Requirement Specification Document* (ORSD) which should include the purpose, scope, implementation language of the ontology network, target group, intended users and requirements in form of *competency questions* (CQs) with pre-glossary of terms (Suárez-Figueroa et al., 2012).

When the first requirements are set the ontology implementation activity can begin. The focus of this stage is to build an ontology using a formal ontology implementation language (Espinoza-Arias et al., 2020). Existing ontology reuse is highly emphasized during this stage and the requirements for choosing ontologies for reuse are explained by Elisa F. & Deborah L. (2019). Other processes during ontology implementation according LOT methodology include ontology conceptualization, encoding and evaluation, while the final outcome is the ontology itself.

The final two and not less important main activities are ontology publication which results in online ontology and ontology maintenance which identifies issues, bugs, etc., and includes ontology evolution process. However, regarding the scope of this thesis, the proposed ontology will be implemented only on a local level, therefore stopping after the second main activity of LOT methodology. Therefore, deeper explanation for the last steps is not given, at the same time indicating that the authors are aware of prerequisites regarding ontology publication and reusability.

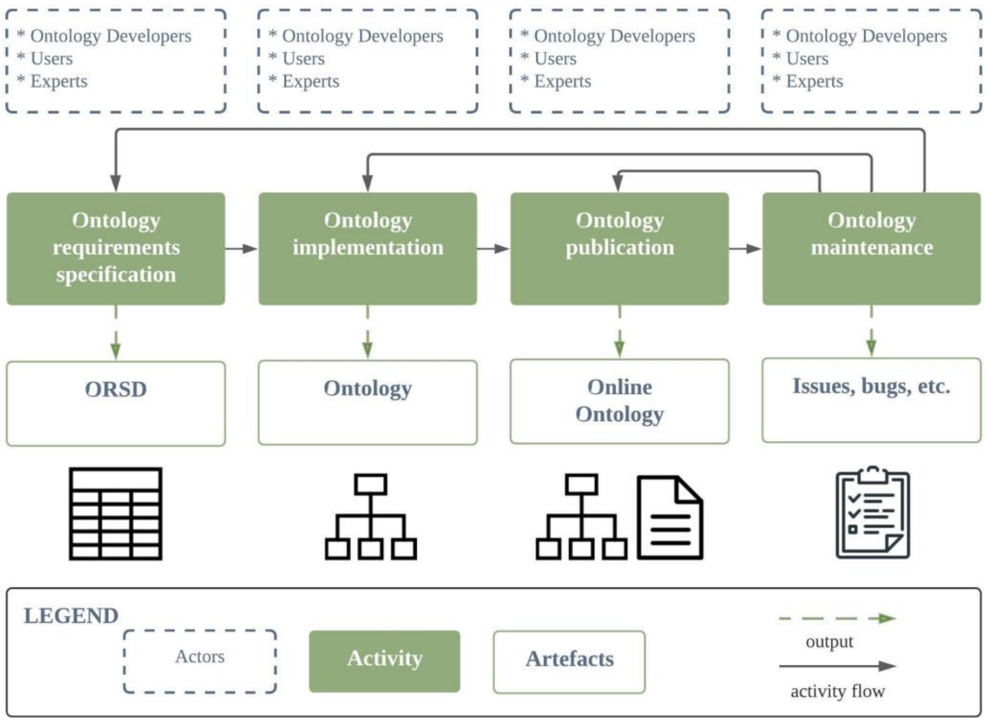


Figure 5: LOT methodology process overview

2.4.4. Prototyping

Prototype is a product of the systems engineering process and can be called a process output for a specific design phase (Lightsey, 2001). The whole prototyping process is based on inputs gathered during the desk research and interviews with industry professionals synthesis to establish requirements and draw system framework. Prototyping is an iterative process looping between requirements analysis, functional analysis/allocation, design synthesis and system analysis/control (Figure 6). During the first iterations paper mock-up/prototype is done in order to imagine how the system should work and how established requirements can be implemented. If the paper prototype looks reasonable, the process can move on for virtual prototype creation. Lightsey (2001, p. 118) describes a virtual prototype as *a "... computer-based simulation of a system or subsystem with a degree of functional realism that is comparable to that of physical prototype"*.

In reflection to this study, only a part of the system framework is chosen for further technical development which is called the first prototype. As the system is presented as a concept it is necessary to analyze all the parts of the system before drawing the final proposition. Therefore, the conceptual phase of the prototype and the "*paper mockup*" is defined as a part of the system, while finally reused continuing the technical development of the prototype.

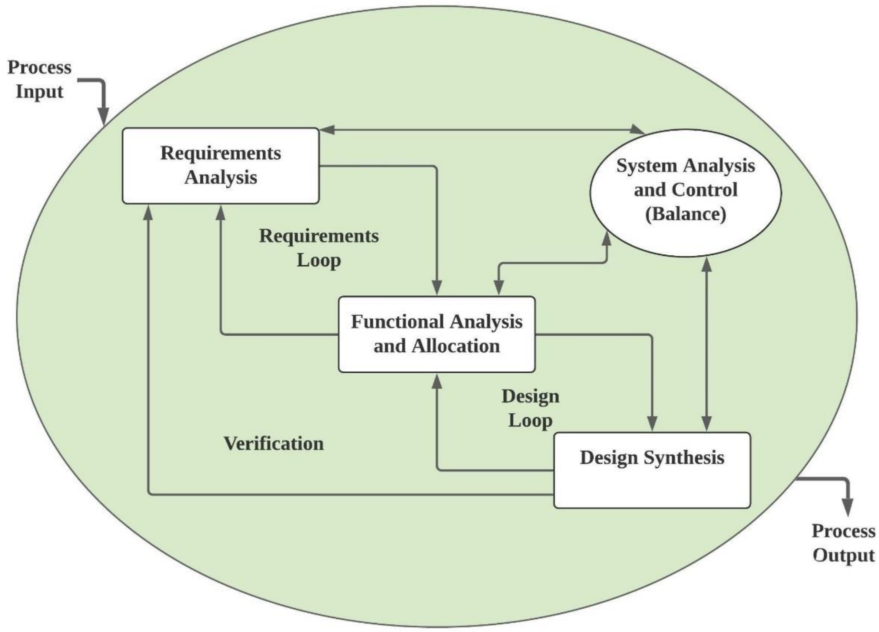


Figure 6: Systems engineering process

2.4.5. *Performance Testing*

In order to validate the results brought by the first prototype performance testing is carried out by the use of *case study* method. The validation procedure is divided in three steps namely, use case description, prototype testing and results analysis. According to Johnson & Christiansen (2014) a *case* is a bounded system dedicated to indicate intended findings and complex things going on in the system. Where *bounded* is meant to emphasize the boundaries of the case.

In reflection to this study, a case is defined with the purpose to simulate a typical situation when the prototype would be in use. The main goal is to replicate a situation most likely to appear in the industry and check how the prototype performs. Therefore, some additional mockup instruments are created to represent user inputs and technical user settings. With that in use the prototype can be tested. The results of the tests then are evaluated based on:

- *Accuracy*. The accuracy of results is tested by comparing the inputs and retrieved results.
- *Usability*. The usability is tested by employing the results in typical user settings.
- *Assessment needs*. Assessment needs are tested while checking if the prototype is sufficient to perform the assessment.

Normally, it is common and required to perform the prototype validation while consulting with the user. However, due to the time restrictions of this study the performance testing is carried out purely technically in order to check the prospect to perform the assessment.

3. Essential Concepts and Definitions

This chapter is dedicated to introducing the most important concepts for this study necessary to proceed further with the desk research. Therefore firstly, the Circular Economy concept is reviewed and introduced including the differences comparing with the linear approach and existing definitions, while further narrowing down to the Circular Economy applications for built environment and circular building definitions. Building Information Management (BIM) is presented as another essential concept, giving the explanation for the main elements important for this study like maturity levels and BIM connection with Circular Economy.

3.1. Circular Economy and Built Environment

In this chapter Circular Economy concept is presented in contrast to current linear model and the benefits of the circular approach. As CE concept is a broad topic and applied to many industries various definitions are explored until one is adapted for the purpose of this thesis. Subsequently, Circular Economy is introduced within the context of built environment, the current implementation stage, and main pillars towards its adaptation. Finally, most referred definitions of Circular Building are given and likewise one is adapted for this project.

3.1.1. From Linear to Circular Economy

With consistently growing World population leading to expansion of consumerist culture, environmental issues and dramatic decrease in raw materials available for extraction, linear model for resource consumption defined in early industrialization times lately received a lot of criticism (*European Commission*, 2020b; *The Circular Economy*, 2014; Ellen MacArthur Foundation, 2013; Munaro et al., 2020). Linear model as well known as "take-make-dispose" model is explained as a process involving industries extracting raw materials for production, manufacturing products and selling them to the consumers, who eventually dispose them (Ellen MacArthur Foundation, 2013). Stahel (2019) indicates maintaining value instead of creating value added, optimization of stock management instead of flows and increased efficiency of using goods instead of producing goods as the main objectives of linear industrial economy. Nevertheless, the tables have shifted remarkably during the past decades as the material price exceeded the price of human labor and environmental concerns pushed the governments to provide regulations addressing the issues (Sariatli et al., 2017).

Numerous countries attempted to solve these problems by implementing recycling-based economy, where the focus point is at the recycling of used products and energy-recovery through incineration of residual flows (van Buren et al., 2016). However, the approach itself has several drawbacks. Incineration destroys the materials/products forever while encouraging wastefulness and recycling is energy intensive, complicated to achieve for composite materials as well as destroys product's integrity and market value (Morseletto, 2020). The main problem with both linear economy and recycling-based economy is that they still involve a raw material input and produce waste while having producers in control instead of owner/user (Stahel, 2019). Stahel argues that these downsides now are one of the drivers to a shift towards the circular industrial economy. In contrast to linear or recycle-based models, circular economy focus on eliminating the waste and shifts the control towards the owner/user. Van Buren et al., (2016) illustrates the difference between the linear, recycle-based economy (called *"economy with feedback loops"* in (Figure 7) and circular economy in Figure 7. Moreover, author lay emphasis on the source of energy used between the first two models in contrast to circular economy model, indicating energy consumption based on raw materials (oil and gas) against the usage of renewable energy, respectively.

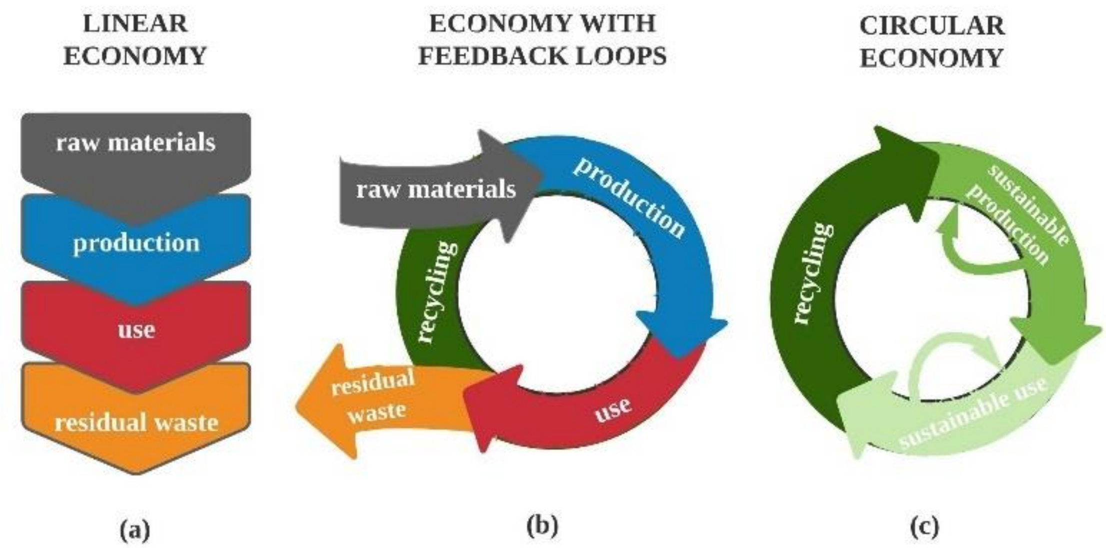


Figure 7: Difference between linear economy (a), economy with feedback loops (b) and circular economy (c). Adapted from (Van Buren et al., 2016)

3.1.2. Circular Economy definitions

Circular Economy (CE) is not a new concept in today's world. Many researchers trace the idea back to the 70s starting with Boulding's (1966) work published in (Dolfsma & Kesting, 2013, p. 335) introducing economy as a circular system, while the term *Circular Economy* is attributed to Pearce & Turner (1991) who explored linear and open-ended system characteristics as well as correlation between economy and natural resources (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Lieder & Rashid, 2016; Murray et al., 2017; Sariatli, 2017). Since then the interest in the phenomena grew substantially (especially in Europe and China) leading to numerous definitions and interpretations regarding Circular Economy notion (Geissdoerfer et al., 2017; Ghisellini et al., 2016; Lieder & Rashid, 2016). In recent years, several authors published review articles on Circular Economy showing the ambiguous interpretations of the concept. Kirchherr et al. (2017) identifies seven previous reviews on Circular Economy and argues that a common understanding is necessary in order to preserve the ideas behind it. Therefore, in his research the author analyses 114 definitions of Circular Economy to draw the final definition which encompass established core principles and aims:

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations." -Kirchherr et al. (2017, p. 224-225)

Together the four strategies (reduce, reuse, recycle, recover) named in the definition above is called the 4R framework. Several other authors propose an expanded version of this framework. For example, (Potting et al., 2017) introduce a 9R framework which was adapted by (Kirchherr et al., 2017) adding a circularity scale moving up the strategy ladder from linear to circular economy (Figure 8). One more important point in Kirchherr's definition is the systems perspective, which defines the level or scale (micro, meso or macro) on which Circular Economy is implemented.

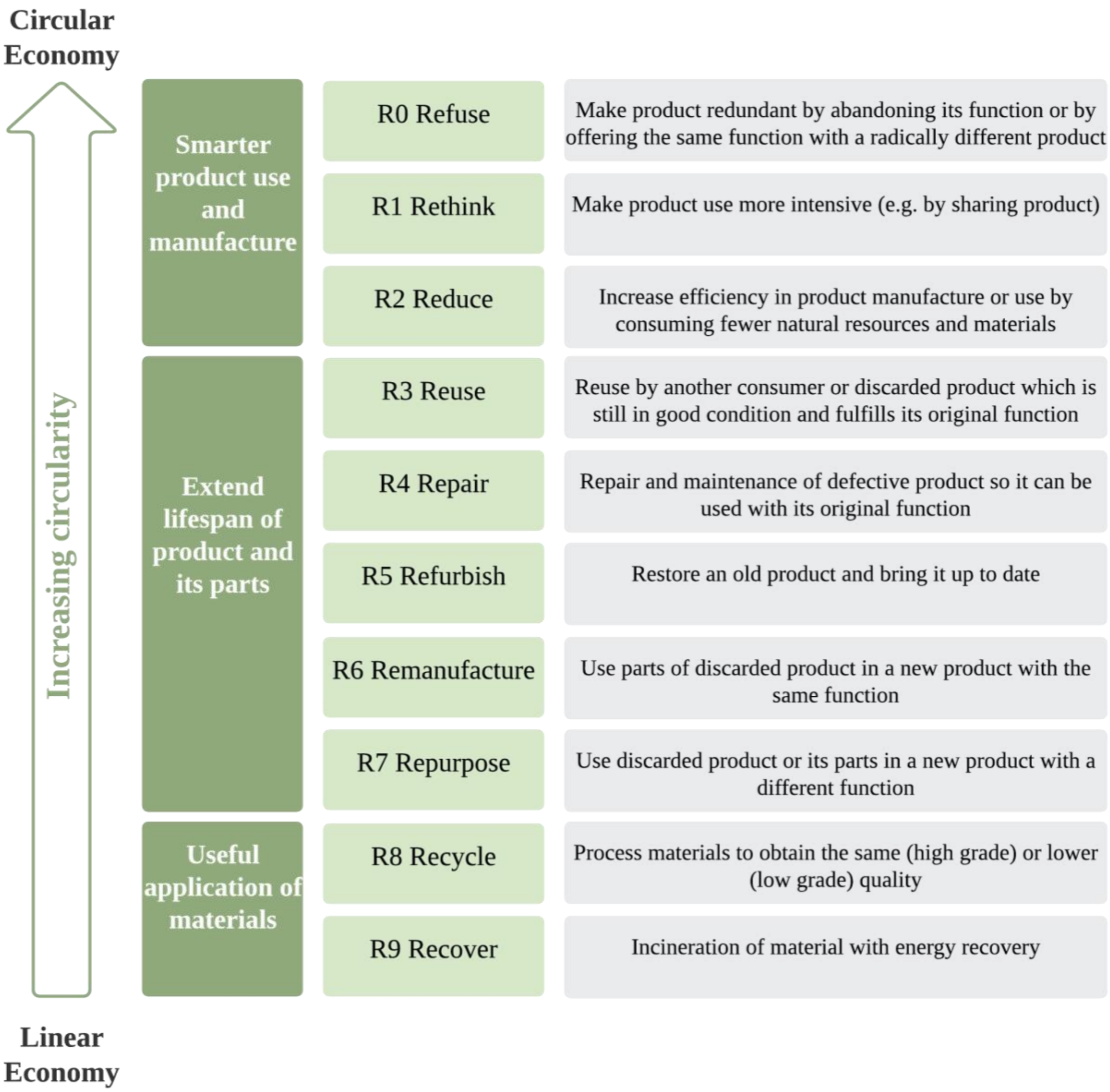


Figure 8: The 9R framework. Adapted from (Kirchherr et al., 2017)

Circular Economy cannot be defined without naming Ellen MacArthur Foundation, which is highly referred by many researchers (Blomsma & Brennan, 2017; Geissdoerfer et al., 2017; Ghisellini et al., 2016, 2016; Lieder & Rashid, 2016; Murray et al., 2017; Sauvé et al., 2016; Slack & Lewis, 2015). Ellen MacArthur Foundation (2013, p. 22) describes Circular economy as *"… an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design."* and propose five principles for Circular Economy:

- *Design out of waste*. Means that products should be designed fitting the biological or technical cycles, designed for disassembly and refurbishment. Biological nutrients should be non-toxic and simply composed.
- *Build resilience through diversity*. Suggests that systems should be built for modularity, versatility and adaptivity.
- *Rely on energy from renewable sources*. Indicates that systems should aim to run on renewable sources.
- *Think in "systems"*. Stresses the importance of understanding how system parts influence each other.
- *Waste is food*. Reminds the significance of bringing the non-toxic products back to the biosphere or improving the quality by upcycling.

These principles are embedded into the Circular Economy definition and illustrated in Figure 9 showing the biological and technical cycles of CE. Ellen MacArthur foundation (Ellen MacArthur Foundation, 2013) identifies *Circular design* as the heart of Circular Economy referring to it as improvements in material selection and product design.

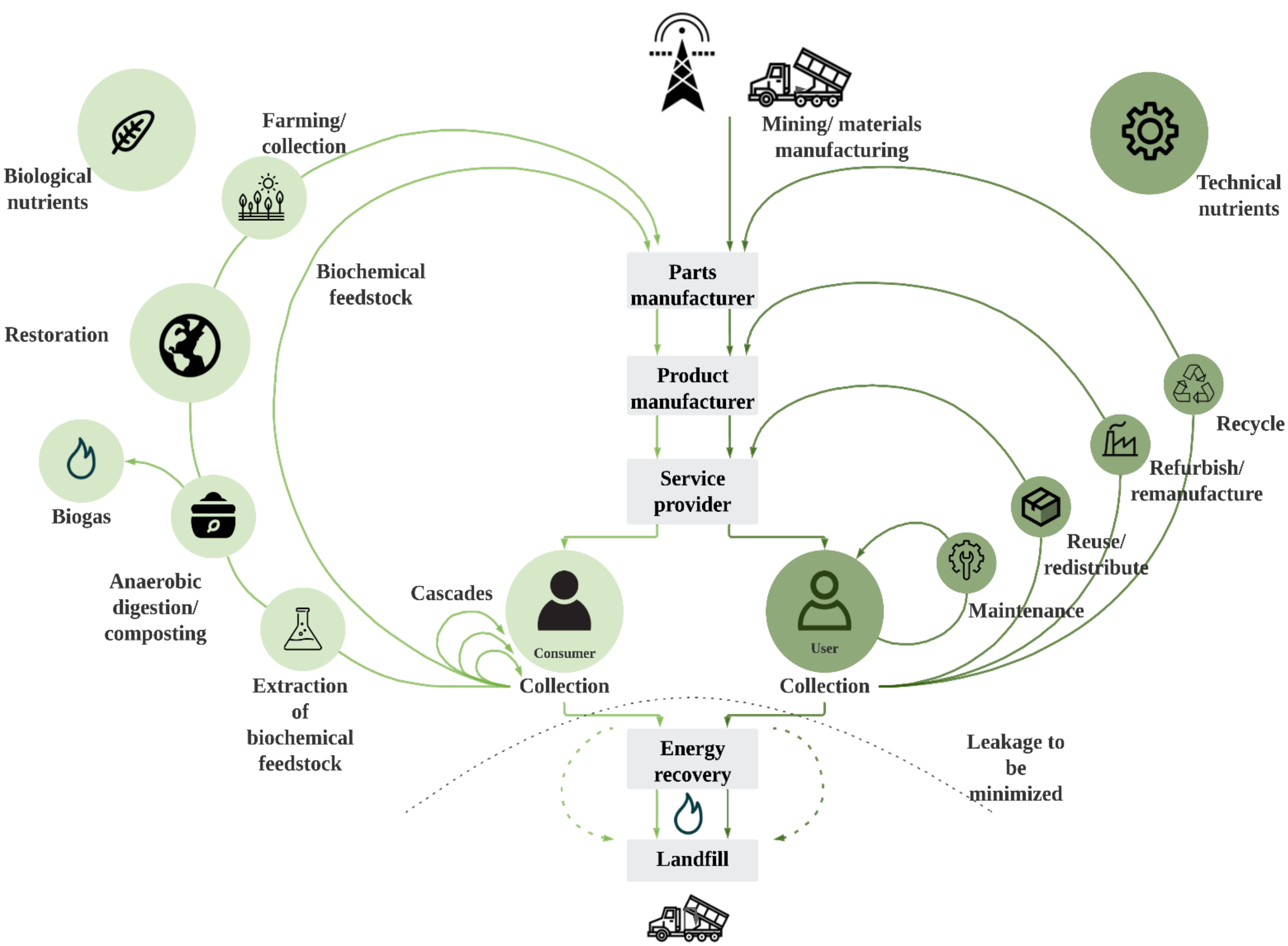


Figure 9: Ellen MacArthur Foundation Circular Economy model. Adapted from (Ellen MacArthur Foundation, 2013)

Looking from governmental perspective Circular Economy has been making its way towards the directives for years. The first Circular Economy action plan by European Union (EU) was released in 2015. In an EU publication *The Circular Economy* (2014, p. 1) it is referred to Circular Economy concept as a response to linear "take-make-dispose" model suggesting that the best way to understand CE is *"… by looking into natural, living systems that function optimally because each of their components fits into the whole"*. Publication emphasize that *Design for Circularity* should be taken as a starting point in the development of any new product or service. European Parliament in *Circular Economy* (2015) defines CE as follows:

"The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended."

Recently *A New Circular Economy Action Plan* (March, 2020) was released where the importance of sustainable design is highlighted as well. The new action plan further suggests some crosscutting actions for Circular Economy indicating research, innovation, and digitalization as transition drivers.

Meanwhile the Danish Government released the *Strategy for Circular Economy* (Ellemann-Jensen & Jarlov, 2018, p. 4) in 2018 where it is stated that *"Circular economy is all about making growth sustainable"*. This release is considered in a close correlation or a branch of *Utilities strategy* introduced in 2016, among others, addressing better utilization of waste. According to Danish CE strategy transition to Circular economy should be led by recirculated products and materials, which value is fully utilized.

As the focus of this thesis is on the technical part of Circular Economy acceleration, delimiting the business, management and governmental perspectives, Ellen MacArthur Foundation (2013, p. 22) CE definition is adapted as it is less cumbersome compared to Kirchherrs' et al. (2017) and more practical then defined by governments.

3.1.3. Circular Economy in Built Environment

Construction industry is identified as the largest consumer of natural resources and around half of the whole world's waste is attributed to it (Ellen MacArthur Foundation, 2013; Mayara Regina Munaro et al., 2020). Moreover, the reluctant ways towards salvage of building materials, energy or demolition materials was identified by many scholars (Cheshire, 2019; Gallego-Schmid et al., 2020; Ness & Xing, 2017; Pomponi & Moncaster, 2017; EMF et al., 2013). Gallego-Schmid et al. (2020) acknowledges that by 2050 built environment is expected to grow by 60% and annual global extraction of primary material is set to triple. Therefore, Circular Economy concept is gaining more and more attention with an intention to lead the AEC industry towards sustainable future. Just in the past two to three years CE for the build environment research interest have tripled (Gallego-Schmid et al., 2020; Joensuu et al., 2020; Mayara Regina Munaro et al., 2020). Nevertheless, it is recognized that currently Circular Economy concept in AEC industry is still in its infancy, which could be addressed to distinctive features of the industry and its products identified as a unique, complex, long-lived and ever-transforming entities (Gallego-Schmid et al., 2020; Mayara Regina Munaro et al., 2020; Ness & Xing, 2017; Pomponi & Moncaster, 2017). Social, economic and environmental pillars are named to lead the way towards sustainable and resilient buildings and cities (Mayara Regina Munaro et al., 2020).

The transition to Circular Economy is considered bi-directional and could be achieved by bottom-up and top-down approaches (Cruz Rios & Grau, 2020; Pomponi & Moncaster, 2017). Top-down approach is directed to governmental level, where the change can be supported by initiatives like offering incentives for salvaged materials, increasing landfill fees or offering credits for companies implementing CE guidelines; meanwhile bottom-up approach is concentrated on companies' effort and could include initiatives for enhancing product durability, leveraging company strategies or increasing design collaboration between project stakeholders (Cruz Rios & Grau, 2020). Pomponi & Moncaster (2017) proposes a framework identifying six interconnected dimensions for building research in Circular Economy (Figure 10). Governmental dimension, as also explained above by Cruz Rios & Grau (2020), should be responsible for tax releases and other initiatives supporting CE; Economic dimension is targeted for a change in ownership or business models transitioning the power from producer to user/owner; Technological dimension is considered as enabler and a key aspect towards huge necessity for circular data management, assessment tools as well as product or manufacturing innovations; Environmental dimension opens a discussion for environmental impact indicator selection; Moving down to the societal dimension CE could be discussed as "sharing economy" stressing the necessity for collaboration between various stakeholders; Finally, the behavioral dimension implies that *"…it is people, rather than technologies, who are the key to embracing circularity."* (Pomponi & Moncaster, 2017, p. 716).

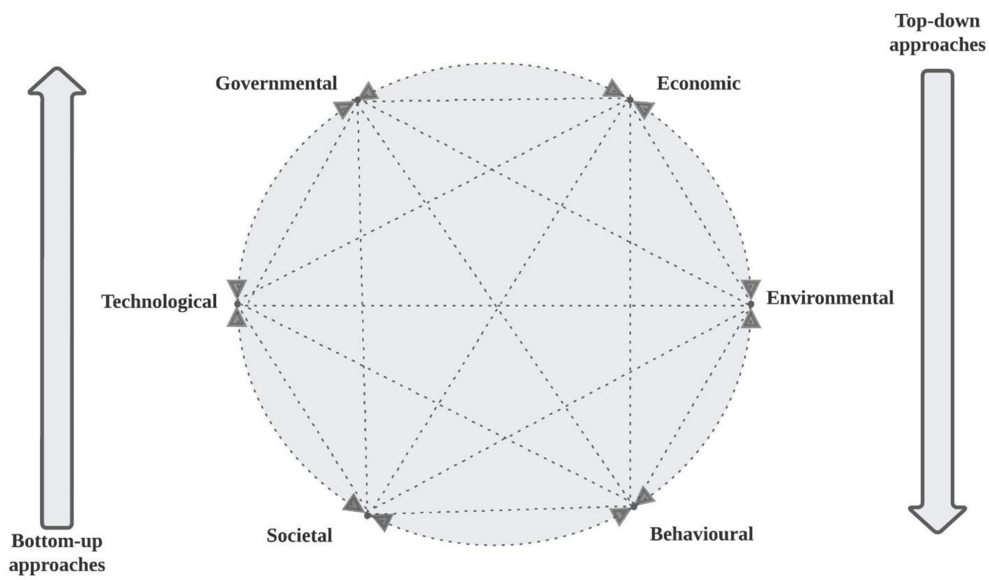


Figure 10: Six dimensions for building research in Circular Economy. Adapted from (Pomponi & Moncaster, 2017)

Similar elements can be seen in Munaro et al. (2020) work, where the authors propose five thematic axes for Circular Economy in build environment. The most research-wise covered topic is found to be recycled/reusable materials (39%), circular transition is second (22%), followed by tools and assessment to support circular buildings (17%), product and building design (14%) and stock and flow analysis of resources and materials (8%). Ness and Xing (2017) suggests a model for a resource efficient built environment which is incorporating three key strategies namely systems innovation, performance management and resource efficiency. Model is combined from eight major components: a closed-loop process for the life cycle of built environments; networks of actors; resources and instruments as the key elements of the urban system; synergies among these key elements; strategies for identifying and managing synergies; and, at its core, desired outputs of a resource-efficient built environment (Ness & Xing, 2017, p. 586). A related model could be also found in *Building Revolutions* (Cheshire, 2019) where author incorporates the technical cycles of Ellen MacArthur Foundation proposed butterfly diagram (Figure 9) with circular business models, waste as a resource and five different design principles: building in layers, designing-out waste, design for adaptability, design for disassembly and selecting materials.

It is easy to see that the transition to Circular Economy is a complex process involving many aspects and there is still a long way for the industry to catch up with the research. Many barriers must be overcome in order to successfully implement the CE concept. In his study Hart et al. (2019) established the main barriers and enablers for Circular Economy in the built environment and divided them in four thematic groups: cultural, regulatory, financial and sectorial. Same barriers are revealed by many other authors as well regularly mentioning issues like lack of stakeholder collaboration, regulatory framework, business models, standardization, design and collaboration tools, common databases, etc. (Debacker et al. 2017.; Gallego-Schmid et al., 2020; Joensuu et al., 2020; Munaro et al., 2020). To surpass these barriers Debacker et al. (2017) propose four required systematic changes: (1) change in the design culture, meaning that buildings should be designed for disassembly using open building systems with an intention to exchange components; (2) intense collaboration within the entire value network, suggesting higher stakeholder involvement during all stages of buildings' life cycle, reaching common agreements and ensuring the quality of reclaimed products; (3) business creation through product service systems, referring to new business models creation and shift from owner-ship to user-ship; (4) centralized management of building and material information, proposing to store building information data in digital and centralized way, crate trust within the value network and use the digitalized information to learn.

In relation to this thesis the authors decided to concentrate on the technical aspects enabling CE implementation in the built environment. Early design stage was identified by scholars as a critical point towards circular building: *"CE should be adopted to select the best strategies and tools during the early stages of design, as this phase is decisive in the overall performance of buildings."* (Mayara Regina Munaro et al., 2020, p. 15). During this stage crucial changes still can be done without high increase in costs. However, to make these modifications possible a strong need for a common database and assessment tools was expressed (Gallego-Schmid et al., 2020; Hart et al., 2019; Joensuu et al., 2020). Therefore, the further desk research for this project is dedicated to uncovering the current practices related to early design assessment from a technical perspective.

3.1.4. Defining Circular Building

In order to define a circular building, we need to look back to the general Circular Economy definitions and frameworks proposed for the built environment. Pomponi & Moncaster (2017) determines two aspects to consider while framing CE in building research perspective: first, short-lived solutions are unlikely to be applicable to buildings and secondly, the useful life phases of the building's life cycle extends to a significant period of time. Therefore, before defining a circular building it is important to address the lifespan of different system components. Pomponi & Moncaster (2017) proposes to look at the building from a systematic point of view on three levels: macro level (seeing buildings as urban agglomerates), meso level (the building itself), and micro level (building components). However, this system division is too general to attach a possible lifespan. Back in the 90s Brand (1995) introduced a "sharing layers" concept where he divided the building system into six layers (Figure 11). Site layer is defined as a geographical setting and set to be eternal. Structure layer entails the foundation and load-bearing elements, skin- is the exterior surfaces while services involves all the communications of the building, electrical wiring, plumbing, etc. Space plan is the interior layout involving walls, ceilings, floors and similar. Finally, stuff is all the things inside the building like chairs, desks, phones, lamps and so on.

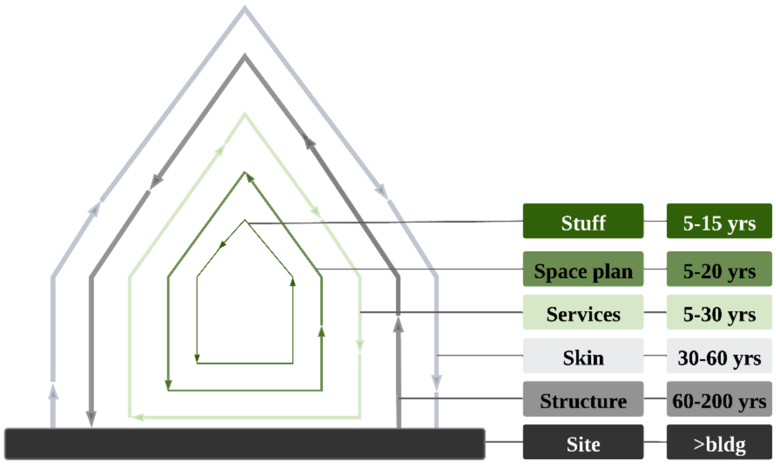


Figure 11:Brands' building layers. Adapted from (Brand, 1995)

Knowing the lifespan of the system components in CE for built environment is very important as it is one of the key elements determining its possible destiny. In his research Akanbi (2018) proved that after 50 years the salvage performance of a building decreases dramatically. As circular building design includes maximizing the usage of available resources, reducing the waste and environmental impact, deciding on when elements are still in good shape to be reused is crucial (Kanters, 2020). There are three main strategies in relation to CE: slowing resource loops (prolonging and intensifying the use of products), narrowing resource loops (reducing resource intensity an environmental impacts) and closing resource loops (restoring or creating new value from used materials) (Gallego-Schmid et al., 2020). Closing resource loops is considered as a main goal for CE by many entities and institutions (Pomponi & Moncaster, 2017).

Pomponi & Moncaster (2017, p. 711) defines a circular building as" *... a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles.".* Meaning that Circular Economy principles should be implemented in the whole life cycle of the building. That being said when describing a circular building all six research dimensions proposed by Pomponi & Moncaster (2017) should be considered (Figure 12). Leising et al. (2018, p. 977) extends the circular building definition explaining CE approach for circular buildings as *"A lifecycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank".*

In the light of this thesis the Pomponi & Moncaster (2017) Circular Building definition is adapted as it is brief and combined with Ellen MacArthur Foundation (2013) definition of Circular Economy reflects well the purpose of further research.

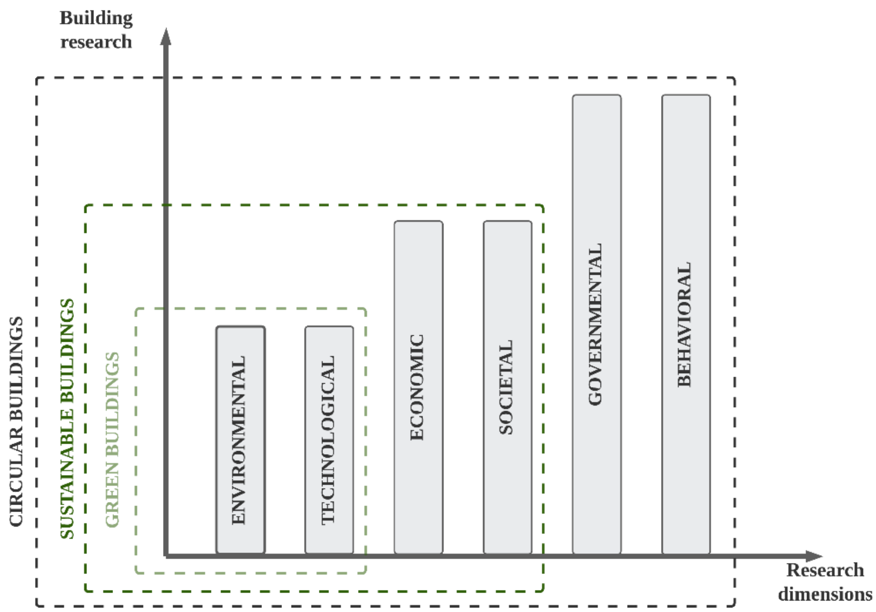


Figure 12: Dimensions incorporated in circular building research and definition. Adapted from (Pomponi & Moncaster, 2017)

3.1.5. Sub-chapter summary

In this chapter the current linear economy approach was introduced and main issues regarding it revealed. The problems concerning the environment and resource scarcity are clear and undeniable. Therefore, some initiatives regarding the problem, like recycling policies were introduced, however the benefits of Circular Economy approach seem to surpass the others. Subsequently, the CE concept was explained, and most referred definitions given. It is evident that up until now there is no common Circular Economy definition, therefore for the purpose of this thesis Ellen MacArthur Foundation (2013, p. 22) definition was adapted:

"The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design."

Further the Circular Economy concept was reviewed in relation to build environment. It was identified that AEC industry is responsible for half of the whole World's waste and it is the second biggest natural resource consumer. That being said it became clear that this industry should be a frontrunner towards the CE implementation.

Finally, the concept of circular building was introduced. An important note was revealed by Pomponi & Moncaster (2017) saying that the solutions regarding Circular Buildings should be log-term as the life-cycle of buildings extends to a significant period of time. Furthermore, the research showed that different building's components have various lifetime. Therefore, Brand's (1995) building layers were explored. Similarly, to Circular Economy a common definition for Circular Building was not found as well. Thus, the definition by Pomponi & Moncaster (2017, p. 711) is adapted saying that a circular building is:

" … a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles."

3.2. Building Information Management (BIM)

Before the advancement of information technology and its applications, the AEC industry relied on the use of 2D drawings to communicate project-related information. As a result, numerous problems associated with such practice have arisen, particularly in the design phase, in which the negative impact is significantly higher in terms of time, cost and ability to provide adequate information for critical design evaluation (Sacks et al., 2018). Moreover, Sacks et al. outlined the role of computer-aided design (CAD) constant development in the transition from 2D drawings to the implementation of 3D models, allowing architects, engineers, contractors, consultants, and owners to include building-related details into the 3D models, including the information dimension which is known as the Building Information Modelling (BIM). Furthermore, they described the building model by its “content” and “capabilities” and distinguished between two BIM implications. First, BIM as a process (building Information Modelling), defined as a *“…modelling technology and associated set of processes to produce, communicate, and analyze building models”* (p-14). Second, BIM as a product (Building Information Model), defined as the result of the modelling activity that reflects the building physical and functional characteristics.

Several definitions and explanations for BIM have been introduced. The definitions can vary based on the user’s perception and the context in which BIM is being used (design, construction, facility management, etc.) (Abbasnejad & Moud, 2013). Five definitions by organizations and institutes for BIM have been gathered and summarized in Table 1.

Table 1: BIM definitions

Source		Definition
ISO 16757-1: 2015		"Construction of a model that contains the information about a building from all phases of the building life cycle" (ISO, 2015)
ISO 29481-1:2016		"use of a shared digital representation of a built object (including buildings, bridges, roads, process plants, etc.) to facilitate design, construction and operation processes to form a reliable basis for decisions" (ISO, 2016)
PAS 1192-5:2015		"discrete set of electronic object-oriented information used for design, construction and operation of a built asset" (PAS, n.d.)
National Institute of Building Science (NIBS)	BIM (modelling)	"Is a business process for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms." (NIBS, 2015)
	BIM (model)	"Is the digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onwards" (NIBS, 2015)
Autodesk		"Building Information Modeling (BIM) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure" (Autodesk, n.d.)

The previous definitions appear consistent with Sacks et al. (2018) statement regarding BIM two implications. Thus, the definitions provided by Sacks et al. are therefore adopted for the purpose of this research and BIM is therefore considered to be both as a process and a product.

3.2.1. Maturity levels

In response to the increased projects' complexity, the AEC industry is pushing for rapid adaptation of BIM in order to overcome the flaws of traditional practices. BIM is being used at different levels, first defined by Mark Bew and Mervyn Richards in 2008 as the "maturity model" (Figure 13). Described by Sacks et al. (2018) the model is divided into four levels in which the AEC industry transition from the traditional fragmented and unorganized practices of information exchange (level 0) towards increasing interoperability through integration of standards and the use of a single shared project model collaborative work leading to common data environment also known as "Open BIM" (Level 3). Nowadays, most of the AEC industry BIM utilization fall within (level 1) maturity category were a combination of 3D CAD and 2D traditional approaches are being utilized for project works.

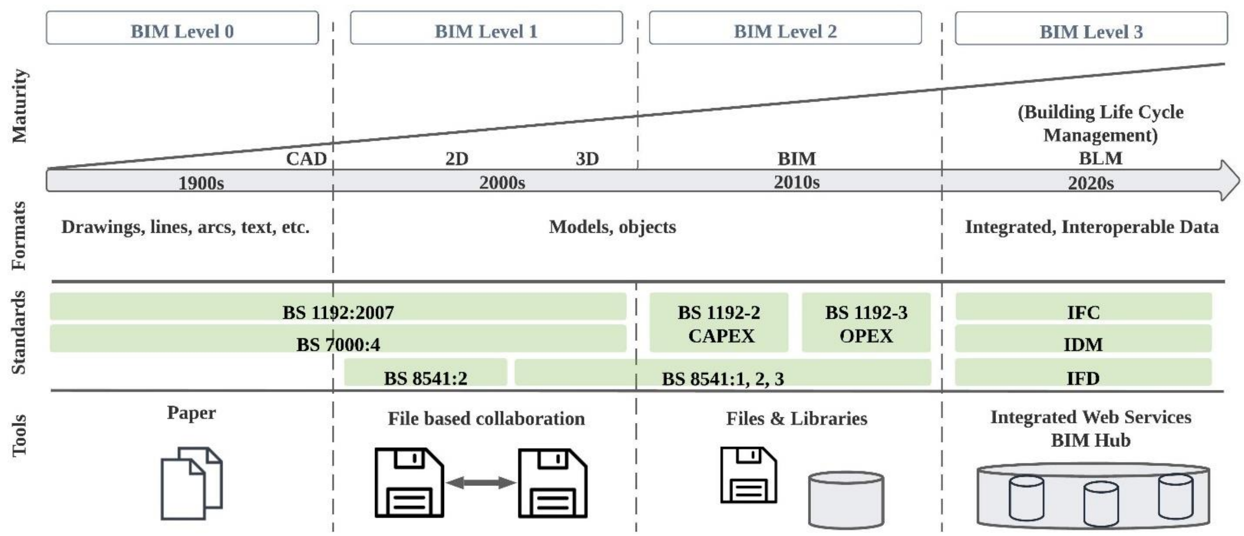


Figure 13: BIM maturity model by (Bew & Richards, 2008). Adapted from (Sacks et al., 2018)

3.2.2. Challenges and Opportunities

Different opportunities associated with the implementation of BIM through the project life cycle were identified and explored by different authors (Chiu & Lai, 2020; Ghaffarianhoseini et al., 2017; Kushwaha, 2016). For instance, (1) Improved visualization and understanding through the utilization of the 3D models; (2) Improved communication and information exchange between different stakeholders; (3) Accurate scheduling and cost estimation; (4) Reduced design errors and improved collaboration with different departments; (5) Improved sustainability and improved building's environmental impact. In a similar manner, Azhar et al. (2012) reviewed potential benefits of BIM implementation on different project stakeholders (owners, designers, contractors and facility managers). They concluded that BIM utilization can improve their work practices through various project life cycle phases.

Despite the benefits offered by BIM, different BIM implementation barriers were identified as well (Ahmed, 2018; Chiu & Lai, 2020; Kushwaha, 2016; Shehzad et al., 2019). For example, (1) Lack of education, training, and BIM experts; (2) High cost of implementation; (3) Absent of governmental legislation; (4) Uncertainty and slow benefits realization; (5) Resistance to change. Moreover, Azhar et al., (2012) identified two main implementation barriers. First, process related barriers in relation with creating and updating the building model, level of responsibility and BIM data ownership. Second, technology-related barriers in relation with availability of BIM standards and interoperability between different BIM applications.

3.2.3. Standards

The literature presented a general understanding of the benefits and limitations for the implementation of BIM, with particular focus on the topic of interoperability as a significant catalyst for an efficient utilization of BIM. It can be defined as information exchange with minimum loss between different BIM software vendors (Borrmann et al., 2018), smooth exchange of information to facilitate automation (Sacks et al., 2018) *and "… the ability of diverse software and hardware systems to work together smoothly, which enables integrated project delivery via BIM model"* (Ozturk, 2020,p.2). To ameliorate the interoperability issues within the AEC industry, Building SMART International (BSI) previously known as International Alliance for Interoperability (IAI) developed sets of standards. For instance, the Industry Foundation Classes (IFC) (ISO, 2018), which is an open neutral data model that facilitates the representation and exchange of building's geometry and related semantics between different software applications (Borrmann et al., 2018; Ozturk, 2020). Explained by Sacks et al. (2018) IFC is based on ISO-STEP, exchanged through STEP Physical File (SPF) format and the schema is modeled using EXPRESS modelling language. Moreover, IFC schema data model can be represented as Extensible Markup Language (XML) using XSD schema encoded as ifcXML format to enhance readability and Web based exchange (BSI, n.d.-a). Additionally, Resource Description Framework (RDF) using ifcOWL ontology enables the representation of building data using Semantic Web and linked data technologies allowing the linkage with other source of data such as material, GIS, sensor, etc. (BSI, n.d.-c). In addition, another BSI initiative with the aim to enhance IFC interoperability by representing its schema using JavaScript Object Notation (JSON), ifcJSON can enhance the web-based data transfer and cloud based BIM applications (Afsari et al., 2017).

IFC can contribute heavily towards a more collaborative work environment. However, due to the increase in project's complexity and higher demands for precise requirements, BSI developed the model view definitions (MVD) as a subset of the IFC data model responding to the high demand of the project's participants for more specialized information exchange (Sacks et al., 2018). Furthermore, Sacks et al. described another standard with the purpose to identify the exchange requirements and the process of the information exchange. The information delivery manual (IDM) which is an ISO standard (ISO, 2016) developed by BSI. It comprises of a process map and exchange requirements that can be used to identify what information is needed, who is responsible for providing the information and when it is needed. Additionally the exchange requirements can be utilized for developing special sets of MVDs (BSI, n.d.-d). Moreover, another core BSI standard was developed with the purpose of linking different terminologies for objects and properties known as buildingSMART Data Dictionaries (bSDD), based on International Framework for Dictionaries (IFD) (Borrmann et al., 2018; ISO, 2007). The previous literature reported three core standards developed by BSI related to data, process, and terms. In addition, another open standard is used to enhance BIM-based coordination such as the BIM Collaboration Format (BCF) defined by Tekla and Solibri and is a BSI standard used to communicate discrepancies in the design between different departments (Sacks et al., 2018).

3.2.4. BIM and Circular Economy

The previously reviewed literature described potential benefits of BIM implementation in terms of communication, data exchange, time, cost, etc. However, only few scholars discussed the potential integration of BIM and CE adaptation. Nevertheless, Charef and Emmitt, (2020) in their review explored potential BIM uses in relation to CE and its implementation in the AEC industry. They identified seven BIM uses related to the creation of 3D models maintaining asset's information through the project's lifecycle, utilizing material passport and material banks to store information related to material components, and conducting circularity assessments to measure the degree of compliance with the CE models. In a similar manner, Aguiar et al. (2019) examined the possible incorporation of BIM and material passports to promote circular design. They suggested two BIM models, a life cycle model and a circular model, which could be utilized to access material related information across different project phases. Furthermore, as mentioned before BIM is utilized for proper information exchange and improved visualization. Thus, the level of development (LOD) for the developed 3D models is an important aspect to be considered. Defined by BIMForum (2019) as *"a reference tool intended to improve the quality of communication among users of Building Information Models (BIMs) about the characteristics of elements in models"*(p.4), it was developed by the American Institute of Architects (AIA) and encompass five levels from 100 to 500. Moreover, BIM can be utilized to facilitate the assessment of buildings at different life phases. According to Soust-Verdaguer et al. (2017) LOD 300 is suitable for the assessment of the environmental impact at early design phase. Similarly, Akbarieh et al. (2020) found through their review that a minimum LOD of 350 is required for a proper planning for the material destination at the buildings end of life stage.

Different studies tackled the limitations of such integration. According to Davila Delgado and Oyedele (2020) standard data models are utilized to capture and share data between different stakeholders. However, they argued that the lack of interoperability in using IFC data model to capture CE principles. Additionally, Charef and Emmitt identified six barriers that could limit the BIM utilization for CE adoption namely (1) Economic; (2) Political; (3) sociological; (4) Technological; (5) Environmental; and (6) Organizational barriers.

3.2.5. Sub-chapter summary

Various literature related to BIM has been reviewed in this section. Multiple BIM definitions were explored, and it was concluded to consider BIM as a process (Building information Modelling) and as a product (Building information Model). Subsequently, the different benefits from BIM implementation were identified along with impediments limiting the adaptation in the AEC industry. Two key barriers have been identified, namely: process and technology barriers. BSI initiatives to ameliorate the interoperability and process related issues were discussed and different standards were addressed. Table 2 reflects the standards developed by BSI standards.

Table 2: BSI standards

Standard	Schema	Extension	Summary
(IFC) - ISO 16739	Express	.ifc	Used for representation and information exchange between different BIM authoring tools, it is based on ISO-STEP and represented using EXPRESS modeling language
	XSD	ifcXML	IFC schema represented in XML format to enhance readability and Web based exchange
	RDF	.ifcOWL	Representation of IFC schema using Web Ontology Language (OWL) which enables to present building data using semantic web and linked data technologies allowing the linkage with other source of data such as material, GIS, sensor, etc.
	JSON	.ifcJSON	IFC schema represented in JavaScript Object Notation (JSON), enhance web-based data transfer and cloud-based BIM applications
(IDM) - ISO 29481	Comprises of process map and exchange requirements allowing the identification of processes and information flow		
(MVD)	Subset of the IFC data model for more specific data exchange		
(bSDD) - ISO 12006.3	Linking terminologies for objects and properties		
(BCF)	communicate discrepancies in the design between different departments		

Furthermore, it was found that only few scholars have addressed both CE and BIM. However, the studies discussed the potential integration emphasized on the role of BIM in promoting the adoption of CE within the AEC industry. In addition, a key point was noted with regard to the level of development for the 3D models and its importance for life cycle assessment. Finally, a gap was identified in relation to the IFC schema and its ability to capture CE concepts.

4. Related Work

This chapter is dedicated to answer the first two sub-questions stated together with the problem formulation. The chapter is divided in three main sections related to the research content namely *"4.1 Circularity assessment and design strategies", "4.2 Material Passports and Banks"* and *"4.3 Semantic Web and Linked Open Data"*. Each of the topics presents the main findings necessary to answer the sub-questions and the chapter is concluded with the identification of the found research gaps.

4.1. Circularity assessment and Design Strategies

Among covering the concept of circular economy (CE) and its useful implementation towards reducing the waste at the same time shifting the current linear economy model to a more circular one, comes the need to define the measurement criteria for CE implementation success, in connection with the building sector. Therefore, this section deals with reviewing the literature and identifying the latest contributions related to circularity assessment encompassing subtopics such as circularity indicators, assessment models, assessment tools and design strategies. Additionally, the reviewed literature assisted in answering part of the problem formulation sub-question one (SQ1).

The review was performed following PRISMA framework (Moher et al., 2009) utilizing two widely used databases, Web of Science and SCOPUS. Two search concepts with their synonyms were established for that purpose (Table 3). The search resulted in 126 hits in SCOPUS and 37 hits in Web of science, 10 total studies were chosen for qualitative analysis while 5 more added during the snowballing process of final set of papers (Figure 14).

Furthermore, *Snowballing* research was carried out utilizing Google Scholar database. According to (Wohlin, 2014) *"It is a good alternative to avoid bias in favor of any specific publisher"* (p.2). Accordingly, a Snowballing protocol was established, Table 4. Three backward and forward iterations were conducted and a total of 47 studies out of 80 fully reviewed were included for this section. The inclusion and exclusion criteria were set the same both for the PRISMA framework and Snowballing research. Finally, the results of both research approaches were compared, and 10 duplicates were excluded, resulting in last set of 52 studies included in this chapter review.

Table 3: Circularity assessment and design strategies search concepts and synonyms

Search concept	Synonyms
Circularity assessment	{"circularity indicator* OR "building circularity indicator*" OR " building circularity model*" OR "circularity assessment tool*" OR "building circularity tool*" OR "BIM-based circularity assessment"}
Sustainable design strategies	{"circular design strategies" OR "circular building design strategies" OR "Circular buildings" OR "design strategies barriers" OR "design strategies opportunities"}

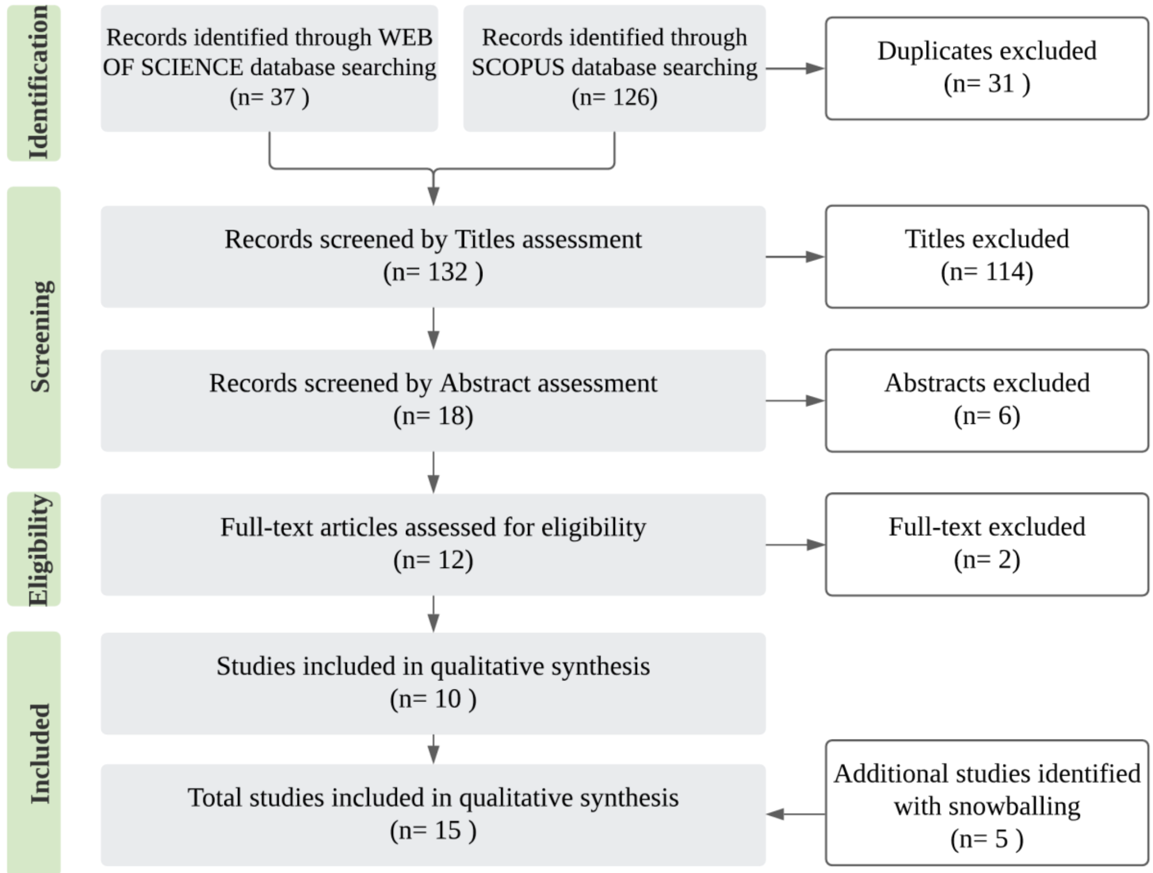


Figure 14: PRISMA diagram showing paper selection process for Circularity assessment and design strategies research

Table 4: Snowballing protocol for Circularity assessment and design strategies research

SNOWBALLING PROTOCOL	**SUBQUESTION SQ1**		
	Research content	Circularity assessment and Design strategies	
	Breakdown	**Circularity assessment**	**Sustainable design strategies**
	Keywords	Circularity assessment, Circularity assessment criteria, Assessment models, Building circularity assessment, Circularity indicators taxonomy, Circularity metrics, Life cycle assessment, circularity measurement, Circularity metric, Circular economy, Life cycle analysis	Design for deconstruction, Building deconstruction, design for disassembly, modular design, Material recovery, Sustainable Construction
	Search strings	{“Circularity assessment” AND “Criteria”};{“Circularity assessment” AND “ Circular Economy”};{“Circular Economy” AND “Construction” OR “Buildings”};{“Assessment methodology” AND “Circular buildings”};{“BIM” AND ”Life cycle	{“Design Strategies” AND “Circular economy”};{“Design strategies” AND “ AEC industry”}; {“Building deconstruction” OR “Design for disassembly” OR “Building adaptive capacity”};{“Material recovery” OR “Material reuse”};{“Sustainable design”

		assessment" OR "Building circularity"} ;{"Building circularity assessment" OR "Building circularity Indicators"};{"Circularity assessment" AND "Circular economy"};{"Circularity indicators" AND "Taxonomy"}	AND "challenges" OR "Drivers" OR "Opportunities"};{"Design for End-of-life"} AND "Construction"}
	Synonyms	Assessment models, Assessment framework; Circularity indicators; Circularity metrics; circularity measurement	Circular design; sustainable design; eco design; Design for End-of-life; Assessment tools; Life cycle assessment; BIM-based assessment
	Databases and publishers included	Google Scholar; Science Direct; SpringerLink; Elsevier Pure; Universiteit Gent; MDPI;	
	Exclusion criteria	1. Not in English; 2. Published before 2010; 3. Not peer reviewed; 4. Do not contain predefined keywords; 5. Non-scientific work; 6. Full text not available;	
	Inclusion criteria	1. Relevant to AEC industry; 2. Language English; 3. Publication date from 2010 to 2020; 4. Peer reviewed; 5. Contains predefined keywords; 6. Scientific work; 7. Availability full text;	

4.1.1. *Circularity indicators*

Growing initiatives towards implementation of CE principles are gaining momentum. However, in order to guarantee a proper measurement of its progress and performance at different levels, support decision makers and practitioners in the direction towards the transition from linear to a circular model, the introduction of reliable indicators is of the essence (Cayzer et al., 2017; Corona et al., 2019; EMF & Granta, 2015; EASAC, 2016; European Commission, 2020b; Saidani et al., 2019). In their review Saidani et al. (2019) endorsed a definition for indicators as: *"quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor"* (p.545). Furthermore, various endeavors for developing and categorizing circularity indicators have been realized, addressing different CE aspects. European Commission (2020b) in their new CE action plan emphasized the need to monitor and expedite the transition towards achieving a more regenerative sustainable model. Thus, new indicators were proposed focusing on areas such as climate neutrality and zero pollution. Similarly, development of indicators associated with resource consumption and its related effects on the environment. Furthermore, Saidani et al. (2019) identified through their review fifty-five sets of circularity indicators developed by scholars, consulting companies and governmental agencies. Likewise, they underlined the importance of perceiving what the indicators assess, in order to be utilized in an adequate manner. Indeed, the indicators were classified into ten categories creating an extensive database to assist in the decision making associated with the Circular Economy implementation. In addition, EASAC (2016) provided variety of indicators with relevance to CE, gathered into six categories (1) Sustainable development; (2) Environmental; (3) Material flow; (4) Societal behavior; (5) Organizational behavior; (6) Economy performance. The indicators provided by EASAC are exhaustive yet are more inclined towards the implementation of CE at the macro and meso levels. As a result it lacks consideration for product performance circularity indicators (Saidani et al., 2017).

The implementation of Circular Economy principles operates into three different levels micro, meso and macro, each level necessitates different sets of circularity indicators (Banaitė, 2016; Zhu et al., 2011) . Further, Banaitė alleged that there are more research studies focusing on circularity indicators at the macro level compared to the other two levels. Nevertheless, different studies were performed tackling product and material circularity performance with respect to CE principles at the micro level (organization, product, and consumers) (Cayzer et al., 2017; Corona et al., 2019; EMF & Granta Design, 2015; Geldermans, 2016; Linder et al., 2017; Moraga et al., 2020; Saidani et al., 2017)

Corona et al. (2019) reviewed assortment of CE metrics related to products and services from various literature, identifying nine circularity assessment indicators. The indicators were classified based on environmental, economic, and social impacts along with utilizing predefined requirements to evaluate the validity, reliability, and utility of the identified CE metrics.

In 2015, Ellen MacArthur Foundation collaborating with Granta Design, noticed the absence of an efficient methodology to evaluate the circularity at product and company levels. Thus, the circularity indicator project has been introduced, developing Material circularity indicators (MCI) within the context of CE. The indicators focus mainly on the technical cycles and material. Specifically, on three main parameters: (1) Amount of Virgin Material; (2) Product Utility; (3) Amount of unrecoverable Waste (EMF & Granta, 2015). Moreover, Moraga et al. (2020) claimed that MCI developed by EMF focus on single product cycle and lack the consideration of time aspect between different material life phases. Thus, they proposed two material circularity indicators “in-use occupation ratio” (UOR) and “final retention in society” (FRS) measuring the potential of material conservation.

Furthermore, Saidani et al. (2017) reviewed existing methodologies assessing product circularity performance in terms of “applicability in industry” and “accordance with circular economy principles”. The review considered five proposed requirements, with the aim to help practitioners figure out best practices and improve product circularity. In a complementary manner, Alamerew et al. (2020) in their study developed a multi criteria evaluation method based on different CE evaluation methods. Their method is based on six main criteria namely: (1) Environmental; (2) Economical; (3) Social; (4) Legislative; (5) Technical; and (6) Business with the aim to help companies evaluate current and circular transformative strategies for product and services. Furthermore, Linder et al. (2017) reviewed existing circularity metrics at product level based on five criteria, (1) Construct validity; (2) Reliability; (3) Transparency; (4) Generality and (5) Aggregation principles. They argued that the product circularity metrics behave diversely among the individual criteria and thus, there is no single robust circularity metric measuring all aspects of product circularity with respect to CE.

4.1.2. Existing Building Indicators and Assessment Models

With a view towards the built environment (BE) European Commission (2020b) described the influence of BE on different sectors of the economy, coupled with a massive consumption of the resources. According to EC the construction sector alone is responsible for extensive waste generation associated with the massive resources consumption and it is considered as s primary contributor to greenhouse emissions. As a result, EC stipulate the path introducing a new "Strategy for a Sustainable Built Environment" fostering building circularity principles, through promoting the utilization of reused construction products, design for adaptability and design for disassembly. As a response for the importance of considering the built environment significant contributor in the transition towards a circular model, different initiatives took place to measure circularity especially in the building sector. In their review Cambier et al. (2020) classified the circular building assessment models on the basis of two parameters. First, the design phase in which it covers feasibility, developed and detailed design phases. Second, assessment model category covering (1) Circular design strategy; (2) circularity score; (3) Environmental impact; (4) Product and material choice; (5) Practical examples; (6) Circular business models. For the purpose of this research, assessment models fall within circularity score category will be further reviewed. Described by Cambier et al. the circularity scoring models are designed to *"objectify the circularity performance of a building or a building element through a scoring or assessment system"* (p.8).

Described by Verberne (2016) a fully circular building should comprise of no primary raw material and comply with the 4R (reduce, reuse, recycle, recover) CE model. Additionally, he distinguished between sets of building circularity indicators, (1) Technical; (2) Functional; (3) Aesthetic and (4) Economic, for the purpose of developing the building circularity indicator (BCI) with the focus on technical and functional indicators to assess the performance of buildings in relation with CE principles. The assessment model is based on EMF (MCI) and relies on four main steps. First, the calculation of (MCI) for each product in the building. Second, the calculation of product circularity indicator (PCI) using disassembly factors. Third, the calculation of system circularity indicator (SCI) utilizing (MCI) and (PCI) to calculate theoretical and practical values and fourth, the calculation of (BCI) by multiplying each (SCI) by the level of importance for the building layer under study. Furthermore, Platform CB'23 (2019) in their guide "Measuring circularity in the construction sector", emphasized on the important role of the construction sector in the transition towards CE. Correspondingly, the "harmonized core method" was introduced based on(EMF & Granta Design, 2015), utilizing sets of indicators measuring the circularity in the construction sector, paying special attention to three main goals: (1) Protecting existing material stocks; (2) Protecting the environment; (3) Protecting existing value.

A case study was conducted by Heisel & Rau-Oberhuber (2020), to evaluate the circularity of a residential unit. They utilized Madaster platform for documenting building related information as well as measuring its circularity using sets of indicators at different life phases. According to (Madaster, 2020) the circularity indicator (CI) is based on (MCI) developed by EMF . Circularity is indicated through a score system for the level of building circularity between 0% being fully linear and 100% being fully circular. Moreover, the assessment is conducted during building's three life phases (1) Construction phase; (2) Use phase and (3) End of life phase (Madaster , 2020). Another study by Cottafava & Ritzen (2020) provided an improvement to the BCI, proposing the predictive BCI (PBCI). They combined the BCI with (1) Embodied energy; (2) Embodied CO_2 and (3) Design for disassembly criteria. In their study, eight buildings were chosen to assess their circularity based on BCI and PBCI. They found that including disassembly weight factors to the calculation of MCI and the amount of building's material details provided, affects the circularity score.

Alleged by Linder et al. (2017), that practically a product level-metric indicators will not have the capacity to hold all features related to the CE transition. Based on that and for the purpose of this thesis technical indicators were considered for further evaluation as summarized in Table 5.

Table 5: Summary of assessment models and related technical circularity indicators

INDICATOR	ASSESSMENT MODEL				
	EMF (MCI)	Platform BC'23	Cottafava & Ritzen	Madaster (CI)	Verberne (BCI)
INPUT					
Quantity of primary materials used	✓	✓	✓	✓	✓
Quantity of secondary materials from reuse	✓	✓	✓	✓	✓
Quantity of secondary materials from recycling	✓	✓	✓	✓	✓
Quantity renewable materials used		✓		✓	
Quantity of scarce materials used		✓			
Product's useful life	✓	✓	✓	✓	✓
Disassembly factors			✓	✓	✓
Toxicity	✓	✓			
OUTPUT					
Quantity of materials for reuse	✓	✓	✓	✓	✓
Quantity of materials for recycling	✓	✓	✓	✓	✓
Quantity of materials sent to landfill	✓	✓	✓	✓	✓
Efficiency of the recycling process	✓			✓	
Quantity of waste generated in the recycling process	✓			✓	

4.1.3. Assessment Tools

An overview of the different circularity indicators and evaluation models relevant to the circularity assessment has been demonstrated in the previous literature reviewed. However, different studies have discussed the utilization of BIM in the assessment process. According to Rahla et al. (2019) BIM can be utilized to aggregate the fragmented data related to the assessment. Furthermore, in their study Akanbi et al. (2018) emphasized on the importance of evaluating the circularity for the building structural component at an early stage of the design. Therefore, they developed a BIM based whole life performance estimator (BWPE) incorporating a mathematical model for this purpose. They evaluated the model using different structural components (steel, concrete, and timber) and provided that different components have different end of life performance in terms of material recovery (reusability and recyclability). In a like manner, Röck et al. (2018) also highlighted the importance of conducting the assessment practices at early design stage. Equally, they used a BIM model along with Dynamo scripts to extract building elements data for the purpose of evaluating the building embodied impact for alterative construction methodologies at an early phase. Similarly, Marzouk et al. (2017) examined the emissions associated with the construction projects taking into account direct, indirect and operational emissions. They also developed a BIM model along with a plug-in for estimating the emissions from various components and assembly alternative, enabling the comparison between the use of renewable and traditional materials in construction. Additionally, Kavitha & Molykutty (2020) analyzed the commercial building glazing material in terms of energy usage, cost and green gas emissions. They utilized a BIM model coupled with a life cycle energy and cost analysis to perform the assessment.

Furthermore, other studies have also discussed the assessment of construction and demolition waste. For example, Lu et al. (2017) developed a BIM based framework for the assessment of the construction and demolition waste generation. They created two external databases and linked them with a BIM model for the assessment of the optimal design scenario and construction methodology in terms of waste minimization. Additionally, Guerra et al. (2020) in their study explored the potential for reuse and recycle of construction waste. They proposed an algorithm coupled with the integration of a BIM model and construction schedules to retrieve project relevant data and plan the reuse and recycle strategy for construction waste. Moreover, Akinade et al. (2015) considered the assessment for both deconstruction of building component and recovery of building material. Thus, they developed a BIM based mathematical model (BIM – DAS) and utilized the data retrieval from the BIM model for the purpose of the assessment. In the same fashion Basta et al. (2020) endorsed the DAS mathematical model and expanded its scope along with the integration of a BIM model and Dynamo to account for steel structure disassembly.

Previous studies have almost exclusively focused on the effectiveness of performing the assessment at early design phase to allow proper management for the construction and demolition waste as well as to plan for the recovery of building's components at their end of life and to enhance its environmental impact. However, there are still a few limitations and shortcomings revealed in the literature. Akbarieh et al. (2020) discussed several BIM based end of life domains through their literature review and identified multiple important issues. First, the framework and prototype developed relies on BIM proprietary tools. Second, a variety of custom parameters and properties were introduced for the purpose of their studies, but as a matter of fact is difficult to implement by BIM tool vendors. Third, the use of application-programming interface (API) to integrate with the BIM tools limits the interoperability. Finally, the study's results were based on case studies, in which question their validity and reliability.

4.1.4. Circular design strategies

"Rethinking product design" is one of the building blocks important for the proper implementation of the circular model (EMF & Granta, 2015). Different studies highlighted the concept of circular design especially design for X or DFX (Go et al., 2015; Moreno et al., 2016; Sassanelli et al., 2020). Go et al. (2015) in their study identified several DFX methodologies with the purpose of improving product sustainability through multiple generation life cycle. Further, they provided a definition for DFX as:

"…a combination of eco-design strategies including Design for Environment and Design for Remanufacture, which leads to other design strategies such as Design for Upgrade, Design for Assembly, Design for Disassembly, Design for Modularity, Design for Maintainability and Design for Reliability" (p.1).

Moreover, several authors tackled the product sustainability improvements by adapting DFX approach. For instance, Rossi et al. (2016) examined various DFX principles related to the eco-design such as (1) design for disassembly; (2) design for remanufacturing, (3) design for recovery; and (4) design for energy efficiency. In the same fashion Sassanelli et al. (2020) reviewed the opportunity of utilizing DFX approaches with connection to Circular Economy and product circularity. They identified sets of DFX approaches categorized into five classes (1) Supply chain; (2) Resource/Energy efficiency; (3) Reliability; (4) Multiple life cycle and (5) Sustainability. Furthermore, Moreno et al. (2016) in their review of literature identified a gap related to the availability of framework for circular design within Circular Economy. Thereby, they analyzed DFX approaches related to sustainability, identifying key circular design strategies (1) Design for circular suppliers; (2) Design for resource conservation; (3) Design for multiple cycles; (4) Design for long life use of products and (5) Design for systems change, for the purpose of developing the framework. Furthermore, Halttula et al. (2020) considered DFX approach in relation with stakeholders participation and how it can minimize waste generate in the construction industry. In addition, they encouraged the engagement of DFX approach at early project phase. This statement concurs with a point addressed by Benachio et al. (2020), in their review identifying opportunities of applying Circular Economy within the construction sector that most of the literature emphasized on the importance of integrating the concepts of Circular Economy within building's projects early design phase. However, Kanters (2020), noted that much of the research areas are inclined towards building materials analysis and performance improvements. Equally, he claimed the lack in the coverage of circular buildings design aspects.

4.1.5. Circular building design strategies

The previous literature reviewed have highlighted the significance of applying DFX approach in connection with circular design. The factor (X) was utilized interchangeably between product improvement, sustainability, and Circular Economy. Additionally, different design strategies were identified paying specific attention to design for multi-life cycles. In this section, the factor (X) will represent circular buildings, therefore, most widely used techniques for circular building design strategies in relation with Circular Economy will be reviewed.

Traditional building design methods continue to focus on buildings and material short term efficiency, as a result of which buildings are less dynamic and are vulnerable to partial or complete destruction at the end of their life phase (Elma Durmisevic & Brouwer, 2002). A new approach is therefore needed to overcome such design inefficiencies. Elma Durmisevic and Brouwer described a sustainable building design to comprise of two requirements (1) the optimization of material and energy and (2) the optimization of construction methodologies and interconnection of its component. In addition, in order to improve building flexibility, they emphasized mainly on increasing building spatial, structural, and material transformation capacity, see Figure 15.

Multi life-cycles design adopts different design methods to sustain the resources utilization in closed loop economy (Go et al., 2015; Sassanelli et al., 2020). In fact, as multi-life cycle approach fits into the framework of building transformation, three design strategies will be further reviewed in particular namely Design for Disassembly, Design for Adaptability and Design for Material recovery.

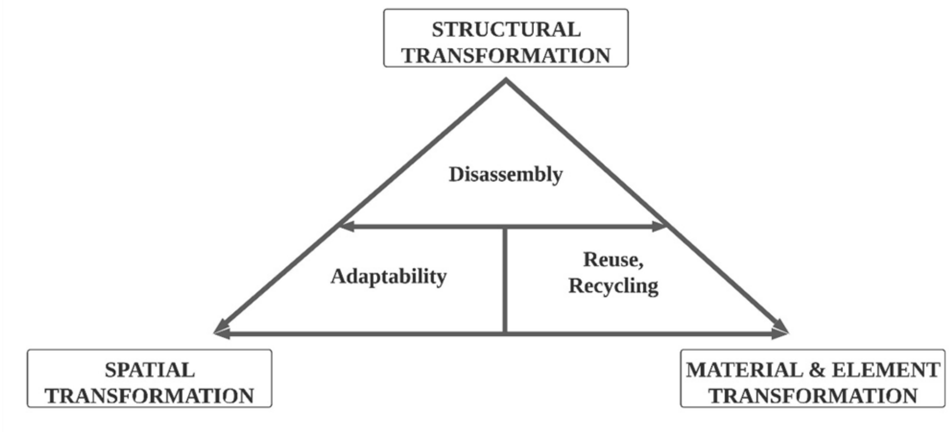


Figure 15: Three dimensions transformation capacity of buildings. Adapted from (Elma Durmisevic & Brouwer, 2002)

Design for Disassembly (DFD)

According to Kanters (2018) the disassembly of buildings and their components at the end of their life phase is not commonly considered at the design level. He argued that the benefits of DFD method are limited not just to minimize the generation of waste but also involves social and environmental benefits. Reviewing the literature, Kanters identified sets of building design concepts that could support DFD for buildings at their end-of-life phase. For instance, the use of modular design, the use of modular structural grids, the separation of mechanical, electrical, and plumbing systems. Moreover, he stressed the importance of selecting appropriate material and connection to facilitate DFD. In a more recent study, Kanters (2020) distinguished sets of objectives related to circular building design based on interviews conducted with different industry stakeholders consultants and architects. The main objectives were specifically aimed at closing material loops through the use of available resources, limiting building waste and mitigating the environmental impact of buildings. Further, he differentiated DFD as the core for circular building design.

Moreover, during their research, Akinade et al. (2017) reviewed three broad factors namely design, building material and human factors associated with DFD, in addition to four focused group discussions with industry practitioners. As a result, 43 DFD related factors have been identified. Accordingly, Akinade grouped the identified factors into five categories (1) Stringent legislation and policy; (2) Deconstruction design process and competencies; (3) Design for material recovery; (4) Design for material reuse and (5) Design for building flexibility. Similarly, Durmisevic (2006) developed a knowledge model with the purpose to evaluate "building transformation capacity". She defined two main criteria for the detachment of building components, namely "independence" and "exchangeability". She identified three transformable configurations, material, technical and physical decomposition. In addition, a set of indicators have been identified for each configuration. Furthermore, each factor has been given a weight factor between zero being worst and one being the best in terms of ease of disassembly.

Design for Adaptability

Despite the fact that the building adaptability concept is being used amongst industry practitioners, there is no general agreement on its definition (Pinder et al., 2017). Pinder et al through their review referred to "*trigger*" and "*impact*" as the two main criteria for defining adaptability. For instance, response to technological or user needs, also the intention to prolong the building utilization lifespan fall within the two criteria identified. Similarly, European Commission (2020a) defined the aim of adaptability is to prolong the building service life through "replacement" and "refurbishment".

Moreover, Schmidt et al. (2010) explored four different themes amongst literature with the purpose to present a definition for adaptability within the built environment. The four themes were centered around readiness for change, mitigate the misfit between building and occupiers, increase the value and short-term as well as long term performance. Correspondingly, he defined adaptability as *"the capacity of a building to accommodate effectively the evolving demands of its context, thus maximizing value through life"*(p-235). In a more recent study by Schmidt (2014) proposed six strategies for building adaptability in particular (1) adjustable; (2) versatile; (3) refitable; (4) convertible; (5) scalable and (6) movable. The proposed strategies further were corelated with Brand's (1995) building layers model as well as demonstrating the type of change and stakeholders involved, Figure 16.

Types of change			Building layers						Stakeholder		
Strategy	Social (cause)	Phyical (affect)	Stuff	Space	Services	Skin	Structure	Site	Enabler	Benefactor	Funder
adjustable	task, user	equipment, furniture	probable						user	user	user
versatile	activity, operations	spatial, arrangment	probable	probable	possible	probable	possible		FM	user	user/owner
refitable	age, technology	component		probable		possible			FM/owner	user/owner	user/owner
convertible	ovnership	function		probable	possible	probable	probable		FM/owner	owner	owner/developer
scalable	market	size, loads				possible		possible	owner	user/owner	owner/developer
*movable	demographics	location	possible		possible	possible	possible	probable	owner	owner/society	developer

*movable was not verified from the research and remains theoretical

Key: probable / possible

Figure 16: Linking model. Adapted from (Schmidt, 2014)

Design for Material recovery

Buildings are not designed with specific intention for material recovery at its end-of-life phase. This can be identified during buildings demolition, were material are not being exploited for further use (Durmisevic Elma, 2006). Noted by Ginga et al. (2020), that construction and demolition activities are responsible for considerable amount of solid waste generated . Therefore, they explored the potential of applying the concept of Circular Economy with a focus on material recovery (reuse and recycle) to mitigate the waste generated from the construction and demolition activities and its effects on the environment. Waste can be reduced when components of a product are designed in consideration of technical or biological material cycles, however, for most materials, the extent of material recovered at their end of life phase are much lower than the extent of virgin material consumption (EMF, 2013). Furthermore, to enhance material or product circularity Geldermans (2016), distinguished two criteria namely "intrinsic" properties related to (material and product characteristics) and "relational" properties related to (building design and use). In addition, he emphasized on utilizing the intersection between material characteristics and design to achieve better recovery value.

Previous literature has shown the implications of considering material recovery aspects in the design phase along with the proper selection of materials. Various efforts to facilitate the implementation towards material recovery in the construction industry have been made. Akadiri and Olomolaiye (2012) managed to develop sets of criteria to support architects and building designers for sustainable material selection. Similarly, Akanbi et al. (2019) developed a mathematical model to estimate the reusability of building materials at their end of life phase. Moreover, several authors have recognized possibilities of using recovered materials in the construction industry. For instance, Smol et al. (2015) proposed the use of sewage sludge ash in construction application such as cement production, brick production, ceramic and glass production and road construction. Additionally, Tallini and Cedola (2018) explored the potential of utilizing waste and by product material as an alternative to the traditional construction material. Accordingly, they identified the potential to improve the thermal insulation performance by using waste material such as recycled glass fibers, recycled textile fibers, ash, rubber waste, etc.

Challenges and opportunities

A number of the existing studies have examined the challenges, drivers and opportunities accompanied with the circular transformation of the construction industry. Much of the reviewed literature have focused mainly on DFD principles as the main driver towards this transformation.

In their review Rios et al. (2015) explored several opportunities of utilizing DFD principles, demonstrating the benefits with respect to the environment, society, and economy. For instance, the contribution of DFD towards closing the material loops can reduce raw material exploitation and decrease the pollution. Moreover, they identified the possibility of creating new job opportunities related to the deconstruction activities in addition to the economic benefits through creating new markets for the recovered material.

A closer look to the literature, however, reveals a number of barriers related to DFD and material recovery. For example, challenges related to the implementation of DFD in the construction industry have been discussed by several authors.

The shift towards a circular building model require other involved industries to coup up with that shift. In fact, this could lead to a gap in the availability of specialized markets and incompatibility between supply and demand for the recovered materials (Kanters, 2020). Moreover, disassembly is expensive and time consuming compared to demolition (Rios et al., 2015; Tingley & Davison, 2011). Additionally, lack of knowledge and experience handling the recovered material can lead to defects during the recovery process. For example, the quality of material is not guaranteed as it is prone to damages during the deconstruction process (Akinade et al., 2017; Rios et al., 2015).

Tingley and Davison (2011) argued that the lack of information from existing buildings associated with DFD can hinder the disassembly process at the building end of life. Manufacturer role is equally important in this regard, as the communication is a key for designers to acquire information related to the products composition and material recovery techniques (Rios et al., 2015). Moreover, standards and legislations can act as a catalyst to foster the DFD implementation. For instance, Akinade et al. (2017) suggested that environmental assessment methods such as LEED, DGNB and BREEM should include more weight for DFD in their assessment to provide stakeholders with incentives to utilize this design approach. Another study by Rasmussen et al. (2019) tackling the environmental aspects comparing both DFD and upcycled material for building construction in compliance with the European standards EN 15804/15978 analyzed the effect of both designs regarding global warming potential (GWP) and identified that upcycling had less impact than DFD.

4.1.6. Chapter Summary

This chapter was concerned with reviewing the circularity assessment principles. Starting with an overview of the various indicators in relation with measuring the transition towards Circular Economy model utilizing different circularity indicators. It was identified that most of the circularity indicators studies were focusing on measuring the performance at the macro level and less on the meso or micro levels. However, different studies have presented the circularity indicators at micro level for product and services based on various criteria and it was observed that there is no single robust circularity metric measuring all aspects of product circularity with respect to CE.

Moreover, the built environment was described as a significant contributor towards the CE implementation. Thus, an overview of the different circularity indicators and assessment models relevant to the building circularity assessment were addressed, and technical circularity indicators were endorsed for the purpose of this research as summarized in Table 5. Additionally, the studies utilizing BIM in the assessment process were explored and such integration proved to be quite useful in carrying out the assessment at early design stage and facilitating the end-of-life evaluation and planning for buildings. However, several gaps and shortcomings were revealed in terms of interoperability and technical considerations of the various BIM software tools.

Similarly, design for X was introduced as an emerging paradigm toward CE implementation, encompassing different design strategies with the focus on Multi life-cycles design. Subsequently it was noted that most studies confirmed on the importance of adhering the building design to circularity concepts which in return facilitates the CE adoption. Different design strategies in relation with circular building were explored. Further, building transformational capacity was discussed and three design strategies were considered. First, design for disassembly was identified as essential for circular building design and two main criteria along with different factors to assess the building component detachment were introduced. Second, design for adaptability as a method to respond to user needs and extend the building life. Third, design for material recovery planning the destination of material at their end of life utilizing CE concepts such as reuse and recycle. Additionally, opportunities and barriers for circular transformation, more specific for DFD were introduced.

Table 6 offers a general overview of the literature and its contribution with regard to circularity indicators, models, tools, and design strategies.

Table 6: General overview of the literature and its' contribution in regard to circularity indicators, models, tools and design strategies

Author	Year	Circularity Indicators	Assessment Models and tools	Circular Design strategies
Elma Durmisevic, & Brouwer, J.	2002			DFD
Durmisevic Elma.	2006			DFD
Schmidt, Eguchi, R., Austin, T., Alistair, S., & Alistair, G.	2010			DFA
Zhu, Q., Geng, Y., & Lai, K	2011	+		
Akadiri, P. O., & Olomolaiye, P. O.	2012			Material recovery
Schmidt, R.	2014			DFA
Ellen MacArthur Foundation	2015	MCI	Material circularity indicator	Material recovery
Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A.	2015	+	BIM-DAS	DFD
Go, T. F., Wahab, D. A., & Hishamuddin, H.	2015			DFX
Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., & Wzorek, Z.	2015			Material recovery
European Academies Science Advisory Council	2016	+		
Banaitė, D	2016	+		
Geldermans, R. J.	2016	+		Material recovery
Verberne, J.	2016	+	Building circularity indicator	DFD-Material recovery
Rossi, M., Germani, M., & Zamagni, A.	2016			DFX
Cayzer, S., Griffiths, P., & Beghetto, V.	2017	+		
Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F.	2017	+		
Linder, M., Sarasini, S., & van Loon, P.	2017	+		
Marzouk, M., Abdelkader, E. M., & Al-Gahtani, K.	2017	+	+	
Lu, W., Webster, C., Chen, K., Zhang, X., & Chen, X.	2017	+	+	
Akinade, O. O., Oyedele, L., Ajayi, S. O., Bilal, M., Owolabi, H. A., Bello, S. A., Jaiyeoba, B. E., & Kadiri, K.	2017	+	+	DFD
Pinder, J. A., Rob, Austin, S. A., Gibb, A., & Saker, J.	2017			DFA
Akanbi, L. A., Oyedele, L. O., Akinade, O. O., Ajayi, A. O., Davila Delgado, M., Bilal, M., & Bello, S. A.	2018	+	BIM based whole life performance estimator	
Röck, M., Hollberg, A., Habert, G., & Passer, A.	2018	+	BIM & Dynamo	
Kanters, J.	2018			DFD
Tallini, A., & Cedola, L.	2018			Material recovery
Corona, B., Shen, L., Reike, D., Rosales Carreón, J., & Worrell, E.	2019	+		
Saidani, M., Yannou, B., Leroy, Y., & Cluzel, F	2019	+		
Platform CB'23	2019	+	Harmonized core method	
Akanbi, L., Oyedele, L., Davila Delgado, J. M., Bilal, M., Akinade, O., Ajayi, A., & Mohammed-Yakub, N.	2019	+	D-DAS	Material recovery
European commission	2020	+		
Moraga, G., Huysveld, S., De Meester, S., & Dewulf, J.	2020	UOR/FRS		
Alamerew, Y. A., Kambanou, M. L., Sakao, T., & Brissaud, D.	2020	+	Multi criteria evaluation method	
Madaster platform	2020	+	Madaster platform	
Cottafava, D., & Ritzen, M.	2020	+	Predective building circularity indicator	
Kavitha, B., & Molykutty, M. V.	2020	+	+	
Guerra, B. C., Leite, F., & Faust, K. M.	2020	+	+	
Basta, A., Serror, M. H., & Marzouk, M.	2020	+	SS-DAS	
Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D., & Terzi, S.	2020			DFX
Halttula, H., Haapasalo, H., Aapaoja, A., & Manninen, S.	2020			DFX
Ginga, C. P., Ongpeng, J. M. C., & Daly, Ma. K. M.	2020			Material recovery
Cambier, C., Galle, W., & De Temmerman, N	2020		+	

4.2. Material Passports and Banks

This chapter is dedicated to introducing the latest contributions in relation to definition and contents of Material Passports as well as for concept of Buildings as Material Banks. It answers a part of problem formulation sub-question two (SQ2). Two widely used databases were screened- *Web of Science* and *Scopus*, in order to identify relevant contributions for *Material Passports and Banks* including the synonyms of concepts (Table 7). The first search results after listing all the synonyms showed 40 results in *Web of Science* and 94 in *SCOPUS*. Following the *PRISMA framework* (Moher et al., 2009) finally 10 studies were chosen for qualitative analysis while 3 more added during the snowballing process of final set of papers (Figure 17).

In order to avoid publisher bias and identify more relevant studies a complimentary research based on *Snowballing* methodology was performed using *Google Scholar* as a primary database (Wohlin, 2014). A *Snowballing Protocol* for this part of research was created and can be seen in Table 8. During three backward and forward iterations a total of 17 papers out of 39 fully reviewed were included to final literature review for both subtopics of this chapter. The inclusion and exclusion criteria were set the same both for the *PRISMA framework* and complimentary *Snowballing* research. Finally, the results of both research approaches were compared, and 8 duplicates excluded resulting in last set of 22 papers included in this chapter's literature review.

Another complimentary research was conducted for this chapter in order to identify existing databases carrying relevant information for sustainability and Circular Economy in built environment. The outcomes of this research can be seen in sub-chapter *"Buildings as Material Banks"* Table 9.

Table 7: Search concepts and synonyms for Material passports and Banks research

Search concept	**Synonyms**
Material Passports	{"product passport" OR "building passport" OR "circularity passport" OR "resource passport" OR "material passport"}
Buildings as material Banks	{"buildings as material banks" OR "material banks"}

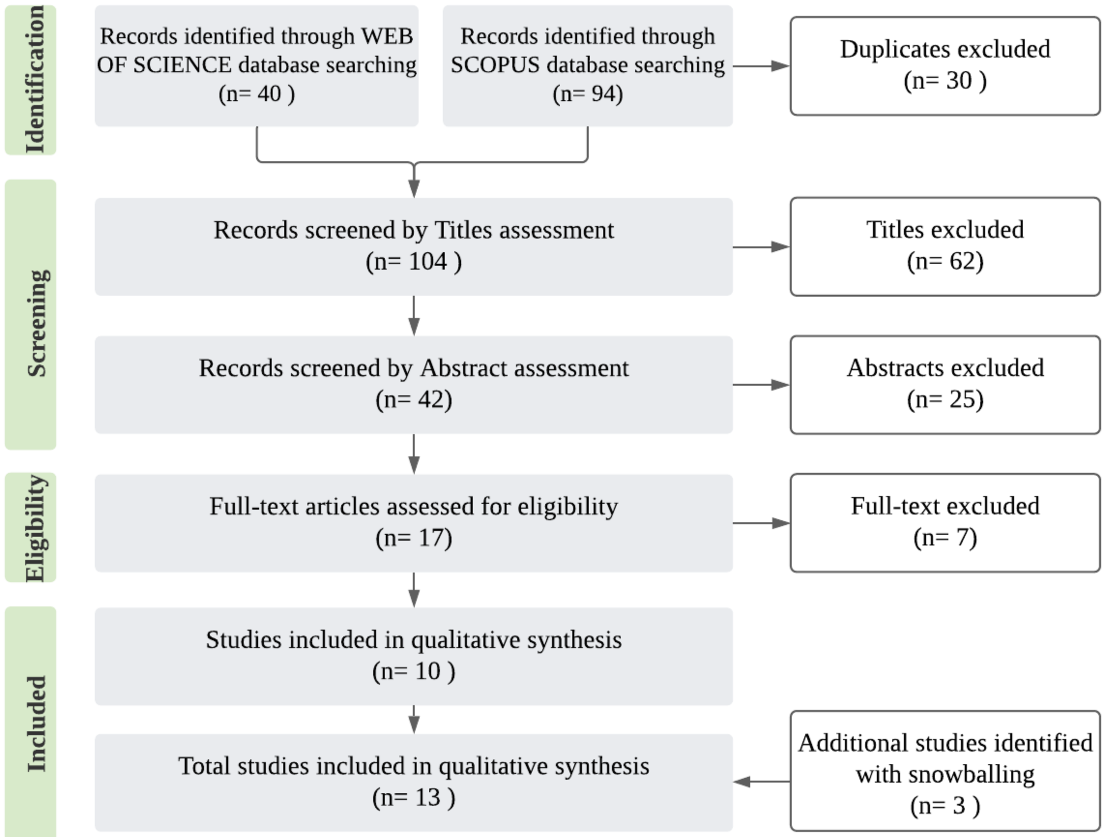


Figure 17: PRISMA framework diagram showing paper selection process for Material passports and Banks research

Table 8. Snowballing protocol for Material passports and Banks research.

SNOWBLLING PROTOCOL	**SUBQUESTION SQ2**		
	Research content	Material passports	
	Breakdown	Defining Material Passport	Buildings as Material Bank
	Keywords	Material Passport; Building material passport; Circular Economy; Bank of materials; Built Environment; Material Bank;	Material Passport; Urban mining; Circular Economy; Built environment, Buildings as Material Bank; Waste management; Reusable components;
	Search strings	{"material passport" AND review}; {"material passport" AND definition}; {"material passport" AND AEC}; {"material passport" AND "built environment"}; {"material passport" AND construction};	{"material bank" AND AEC}; {"material bank" AND "built environment"}; {"material bank" AND building}; {urban mining}
	Synonyms	Product passport, building passport, circularity passport, resource passport	Urban mining, building stock

	Databases and publishers included	Google Scholar; Science Direct; IOP science; SpringerLink; Elsevier Pure; Universiteit Gent; MDPI;
	Exclusion criteria	1. Not in English; 2. Published before 2010; 3. Not peer reviewed; 4. Do not contain predefined keywords; 5. Non-scientific work; 6. Full text not available;
	Inclusion criteria	1. Relevant to AEC industry; 2. Language English; 3. Publication date from 2010 to 2020; 4. Peer reviewed; 5. Contains predefined keywords; 6. Scientific work; 7. Availability full text;

4.2.1. Building Material Passports

Data collection and documentation is vital in order to sustain residual value of materials, products and components as well as to ensure effective stakeholder collaboration in Circular Economy (L. M. Luscuere, 2017). However, current practices and existing certificates like Environmental Product Declaration (EPD), Material Safety Datasheets (MSDS), quality declarations, security measures, lists of material and substances or performance properties lacks information supporting resource productivity (M Honic et al., 2019a; Luscuere, 2018; Munaro et al., 2019). Hansen et al. (2018) distinguish the focus of EPDs or MSDS compared to Material Passports (MP) explaining that MP concentrates more on the value of high-quality material flows instead of emissions. As material circulation and waste elimination is the goal for Circular Economy, material passports are named as CE enabler and a key element for early design assessment (Meliha Honic et al., 2019c). As a concept MP is not new, it had different naming during the history. The term "building passport" was firstly introduced by Eichstädt (1982), followed by other researchers like Turnbull (1993) calling it "product passport", Hesselbach et al. (2001) "recycling passport", de Brito et al. (2007) and Damen (2012) "resource passport", Maersk (2011) "Cradle to Cradle passport", Luscuere at al. (2017) "circularity passport", while "material passport" was introduced by McDonough et al. (2003) and further described by Hansen et al. (2012). Nevertheless, up until now there is no clear definition or common standard for the concept of Material Passport (Miu, 2020).

In 2015 project BAMB was initiated under European Union program "Horizon" with an intention to create a common Material Passport Framework and database for built environment. Project BAMB defines Material Passport as *"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 & Lang, 2019, p. 3). Heisel & Rau-Oberhuber (2020, p. 2) expanded the definition explaining Material Passport as a digital dataset of a specific building, providing a detailed inventory of all the materials, components and products used in a building, as well as detailed information about quantities, qualities, dimensions, and locations of all materials. Meanwhile Honic et al. (2019a) proposes a similar definition emphasizing on recycling potential as well as environmental impact as part of MP. Luscuere (2018, pp. 369–370) gives a more technical explanation saying that *"MP is a digital report containing CE-relevant data that is entered into and then extracted from a database in the form of reports customized to the needs of diverse users."*. In relation to this thesis project BAMB definition is adapted as it is brief and clearly states the purpose of a concept.

Heinrich & Lang (2019) identifies an information gap of material and product information and stress the need for a standardized method for data collection throughout the whole building's life cycle. 3XN & GXN Innovation (*Building A Circular Future*, 2016) suggests five principles to consider in a Material Passport: (1) Documentation should include all relevant information, be accessible and state clear information ownership; (2) Identification should be ensured with unique IDs and linked to a database; (3) Data and database should be constantly updated and maintained; (4) Safety procedures should be defined for all phases of building life cycle; (5) provide guidance and instructions for interim state. Furthermore, it is important to note that a Material Passport should carry information relevant to all phases of building life cycle (Meliha Honic et al., 2019c). Honic et al. (2019a) defines the scope of MP (Figure 18) naming Material Passports as an analysis and optimization tool during the conceptual design phase and stress the importance of this time for building's performance regarding the possibility to make changes for environmental impact and waste management. Regarding the MP in relation to building's life cycle this thesis focus is on *Conceptual Design* and *Preliminary Design* stages (MPa and MPb).

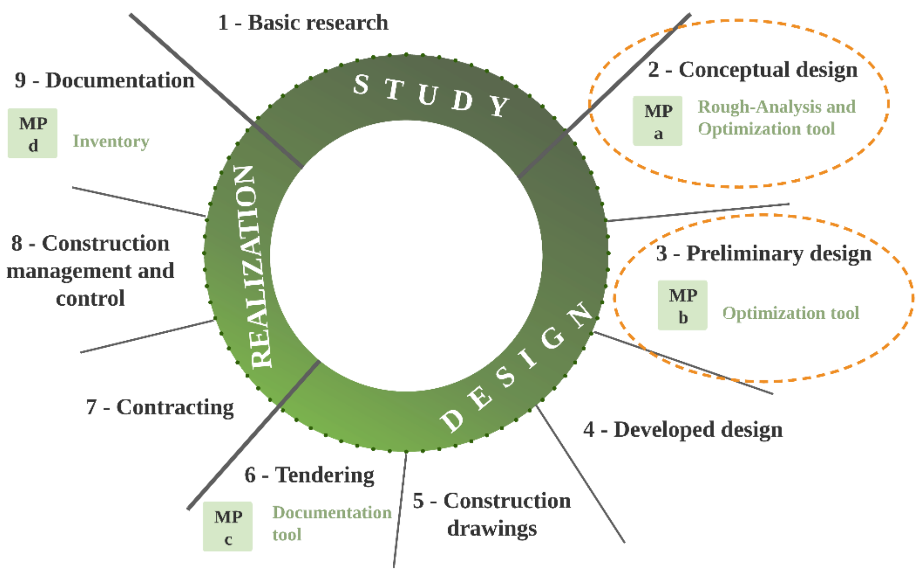


Figure 18: Scope of the Material Passport and thesis focus. Adapted from (Honic et al., 2019a)

Up until now there has been several contributions from scholars, industry and governments proposing structure and contents for MP. Miu et al. (2020) analyzed latest research contributions (including EPDs) of the past ten years regarding the characteristics for material documentation and identified five most commonly proposed: product type/description, product resource composition, product location, product recycling potential and disassembly instructions and disposal. Damen (2012) proposed 25 characteristics for Material Passport, dividing them in five categories: (A) general scarcity-related information needs, (B) mining-related information needs, (C) product-related information needs, (D) company internal information needs and (D) technology-related information needs. Geldermans et al. (2016) was analyzing intrinsic and relational properties of circular materials and products and suggested seven data categories to address in order to assess the circularity potential among others naming the composition, performance and connections applied for materials and products. Verberne et al. (2016) suggested a Circular Bill of Materials (BOM) which include main information about the product (name, ID) as well as its utility lifespan, composition, reusability, etc. supported by important parameters necessary for deconstruction like separability, functional dependence, connection type and so on. Different, than most of other MP propositions, BOM concentrates more on resource reusability than emissions. Munaro et al. (2019) as well proposed a structure for MP arguing that it must contain information on quality, safety, use and operation, disassembly, reuse potential, history of checks and traceability of materials. Meanwhile Almusaed et al. (2020) studied a more specific case in order to propose a material passport needed for buildings in hot climates. During his research most commonly used construction materials were analyzed in relation to existing material passports.

Netherlands can be named as one of the biggest contributors in Europe referring to Circular Economy, currently suggesting a couple of governmental and non-governmental platforms. EPEA Nederland B.V. (EPEA *Nederland*, n.d.) is considered as a forerunner suggesting a MP based on six circularity values: material health, material sourcing, dismantlability, embodied carbon footprint, material recovery and separability. Other Dutch platforms like CIRMAR (*Cirmar*, n.d.) or Turntoo (Turntoo, n.d.) could be mentioned as EPEA successors proposing related variations (L. Luscuere, 2018). BIM-based Material Passports as well takes a big part of research these days (Meliha Honic, Kovacic, & Rechberger, 2019b). Meanwhile, Product Data templates and Sheets (*CIBSE - Building Information Modelling - BIM*, n.d.) are structured documentation directed to manufacturers in order to retrieve product data for BIM models. Still, in relation to Material Passport itself, project BAMB is considered as a main platform proposing a universal MP structure for all stages of building's life cycle (L. Luscuere, 2018). BAMB passport includes vide range of information like product physical/chemical/biological properties, material health, product and system IDs, production/ design data, transportation/ logistics data, construction/ use/ operation data, disassembly/ reuse related data, etc. (Heinrich & Lang, 2019).

Evidently there are numerous initiatives towards definition, structuration and implementation of Material Passports, however the success of MP depend on multiple perspectives. Munaro et al. (2019) expose the main challenges for Building Material Passport (BMP) implementation and divides them in three groups namely politics, commercial and social. Many of the challenges were addressed by other scholars as well, especially the lack of standardization and regulations (Benachio et al., 2020; Meliha Honic, Kovacic, Sibenik, et al., 2019c), complexity of materials/ systems/ components (L. Luscuere, 2018), intellectual property of materials and data related to the product (Meliha Honic, Kovacic, Sibenik, et al., 2019c), lack of collaboration and stakeholder management practices (Hansen et al., 2018; Jayasinghe & Waldmann, 2020), etc. Meliha Honic et al. (2019c) suggested data and stakeholder management framework (Figure 19) in order to tackle these challenges while stressing the importance of collaboration between AEC organizations, regulative bodies and industry. Clearly all the parts are equally important and require immediate attention in order to implement MP as soon as possible and make them effective. Nevertheless, regarding the scope of this thesis, further research is focused on the industry part responsible for data management and partly covering AEC organization part in order to analyze early design workflows and propose appropriate assessment tool.

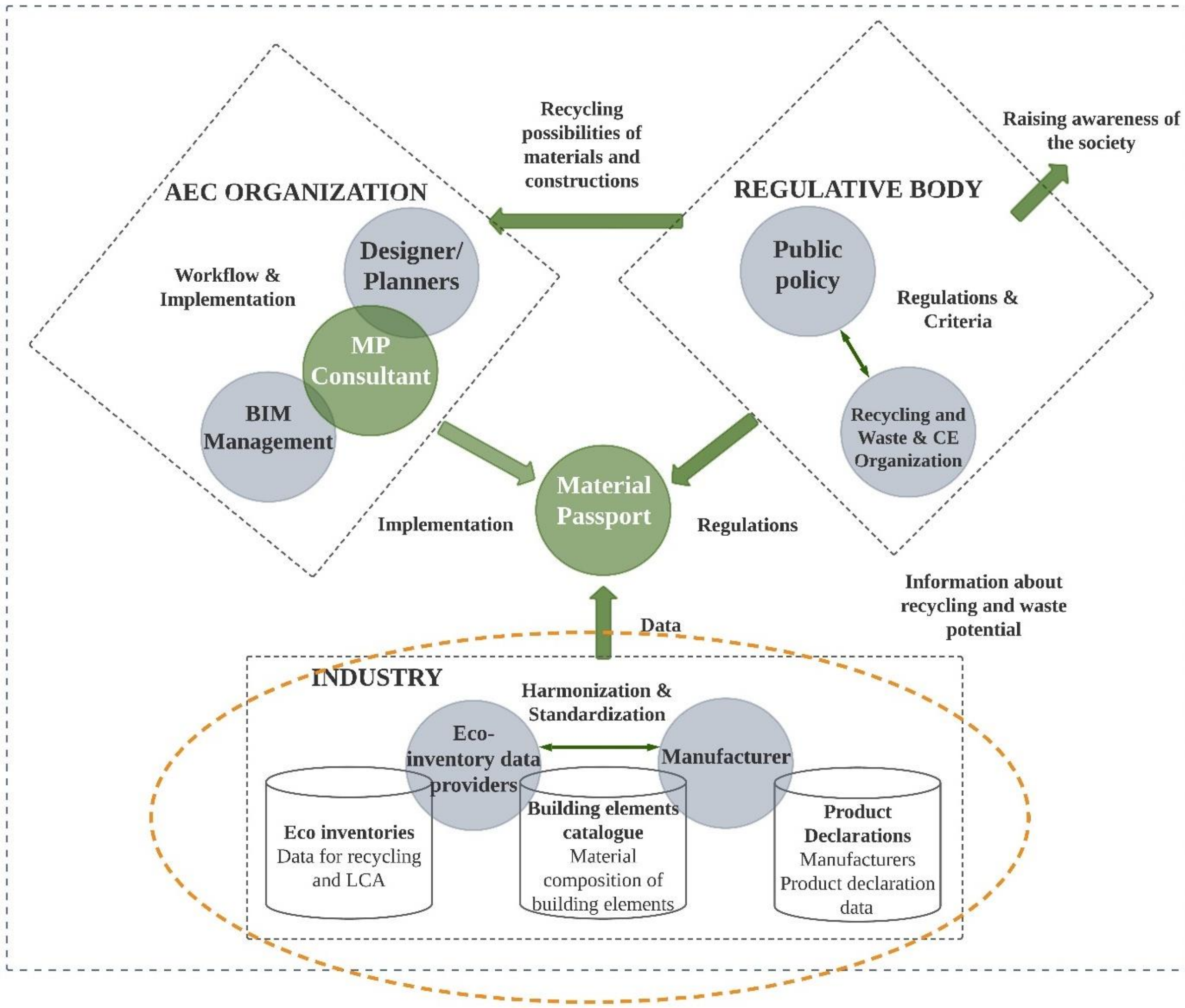


Figure 19: Data and stakeholder management framework with circled thesis focus. Adapted from (Meliha Honic, Kovacic, Sibenik, et al. (2019c)

4.2.2. Buildings as Material Banks

Having Material Passports or any component/material data defined comes the need for a database in order to store it in a convenient manner and ensure easy data access. Addressing this need concepts as *Urban Mining* or *Buildings as Material Bank* have emerged. The term Urban Mining goes back to the 80s introduced by Munro et al. (1984). Cossu and Williams (2015) explained Urban Mining as: *"the process of reclaiming compounds and elements from any kind of anthropogenic stocks, including buildings, infrastructure, industries, products (on and out of use), environmental media receiving anthropogenic emissions, etc."*. Meliha Honic et al. (2019c, p. 1) identifies Urban Mining as one of the main strategies for Circular Economy among others like landfill mining or waste minimizing. Nevertheless, in recent years a new concept *Buildings as Material Bank* arose as project BAMB (2015) under EU project Horizon. Benachio et al. (2020) argues that in Circular Economy models, at the end of building's life cycle materials should be reused and their components deconstructed to act as material banks for new buildings. The tight relation and necessity for material banks can be seen even in some Circular Economy definitions. For example, Leising et al. (2018, p. 977) defined Circular Economy as a *"lifecycle approach that* *optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank".*

Cai and Waldmann (2019, p. 2022) explore the concept of material and component bank addressing to it as *"a manager who organizes the transfer of materials and components extracted from demolished or deconstructed structures to a new structure"*. The authors identify the key businesses of the bank including assessment, conditioning and storage, and certification of materials. Extra emphasis is laid on certification as it should provide an insurance or guarantee for reused materials/components ensuring future reusability, residual load-bearing capacity, assembly-ability, etc. Subsequently Cai and Waldmann determine the need for a detailed database carrying information related to materials/components that would safely store the information for a long period of time in reflection to significant lifespan of buildings.

Several authors suggest solving the issue concerning the need for material bank database relying on BIM-based solutions. For example, Jayasinghe and Waldmann (2020) proposed a web-based application that stores the information extracted from BIM model in MYSQL database and allows the user to query the database by project ID to retrieve the information on different materials (and their properties) used in the building. Meanwhile Honic et al. (2019b) propose a similar approach to generate material passports which later could be stored in an external database. This should be done by populating BIM model with predefined building elements which are later structured using BO (Building One) material inventory and analysis tool and populated by additional recycling and LCA data from the Austrian Institute for Building and Ecology. Another suggestion from Meliha Honic (2019d) relies on BIM model data as well, but this time two more external databases namely concrete building catalogue *baubook* and Cross Laminated Timber (CLT) catalogue *dataholz* are employed. The data from external databases is connected using Austrian tool Eco2Soft while finally everything is stored in MS Excel format. Bertin et al. (2020) introduced one more BIM-based solution for load-bearing construction reuse with LCA integration based on Microsoft SQL. Author concluded that solution could be ran both as open-source or proprietary database while showing that each of the approaches caries its own benefits and drawbacks. Different approach was proposed by Gepts et al. (2019) suggesting to combine two existing databases in order to explore the potential of building as material banks. Nevertheless, the solution was based on very limited datasets relevant only for specific region in Belgium and technical implementation details were not given.

However, as it was expressed by Cai & Waldmann (2019) material banks should serve for a significant period of time and be easily accessible by various stakeholders to make a real use of it. Furthermore, Jayasinghe and Waldmann (2020) identified that BIM models bring a data management challenge due to a high number of elements. Therefore, storing information in BIM models is not a practical solution. That being said, external database like project BAMB *(BAMB, 2020*) is essential. It is important to mention, that currently there are several external databases carrying relevant sustainability/circularity information about buildings' materials/components, however none of them can provide all the necessary information for building circularity assessment. For example, databases like Exiobase (Bjelle et al., 2019) or IMPACT World+ (*IMPACT World+*, n.d.) provide huge amount of data related to product input, output, flows or sustainability indicators from various countries, however the data is statistical and not specific to particular product. Some databases like ProBas (*ProBas*, n.d.) provide information only for products and materials, but not building components. Other issue is faced related to closed or paid license databases as Ecoinvent (*Ecoinvent*, n.d.), LC inventories (*LCI*, n.d.) , LCDN (*Dataset*

Entry-Level Compliance, n.d.) or SundaHus (*SundaHus*, n.d.), which means that the user would need to pay for multiple licenses to find additional data. Quartz (*Open Data for a Healthier, More Sustainable Future*, n.d.) database provide information only on sustainability factors and is limited to 200 products. Highly used for LCA (Life cycle Assessment) are open databases like Oekobaudat (*Database ÖKOBAUDAT*, n.d.), Ibu Data (*IBU.Data*, n.d.), EPD International Data Hub (*International EPD® System - Data Hub*, n.d.), EPD Italy (*EPD Italy*, n.d.) or EPD Norge (*EPD Norway*, n.d.). These databases as well are concentrated on sustainability measures, but there could be some technical circularity assessment related measures found. Furthermore, even in a same database some products carry more information than others. For example, a wooden door passport (as a standardized product) would contain more information than a precast concrete column, which is more fluctuating from project to project. Table 9 shows an overview of several databases mentioned before. Databases were chosen based on relevant information embedded and open access (except SundaHus database). Table 9 illustrates both sustainability related data and data relevant to technical indicators discussed in Assessment Indicators chapter.

Referring to missing connection between databases, there is some effort done there as well. Tools like Open LCA Nexus(*OpenLCA Nexus: The Source for LCA Data Sets*, n.d.) or InData (*InData*, n.d.) provide query interfaces connecting several datasets mentioned before. Project BAMB also is on the way to deliver a web-based tool offering product Material Passports combined using information from various datasets. BAMB aims to provide all necessary information for Circular Economy implementation in built environment, but as the project is not completed yet there are still gaps to fill. However, in the current version of the BAMB passport it is visible that there are more technical indicators available than any other reviewed database (Table 9) and sustainability measures are covered by linking EPDs, MSDS and other data sheets.

*Table 9: External databases comparison (" * " symbol marks information that is partialy included)*

INDICATOR	Exiobase	SundaHus	Oekobaudat	Quartz	Ibu Data	BAMB	EPD Internatinal	EPD Italy	EPD Norge Digi	IMPACT World+
ACCESSIBILITY										
Open/Free	✓		✓	✓	✓	✓	✓	✓	✓	✓
Currently available for use	✓	✓	✓	✓	✓		✓	✓	✓	✓
SUSTAINABILITY INDICTORS										
Carbon footprint	✓	✓	✓	✓	✓	Information retrieved from linked documments like EPDs, MSDS, technical datasheets.	✓	✓	✓	✓
Water footprint	✓	✓	✓		✓		✓	✓	✓	✓
Land footprint	✓									✓
GWP	✓	✓	✓	✓	✓		✓	✓	✓	✓
Primary/secondary energy use	*	✓	✓	✓	✓		✓	✓	✓	✓
Renewable energy use		✓	✓	✓	✓		✓	✓	✓	✓
Life cycle included		✓	✓	✓	✓		✓	✓	✓	
Materials for energy recovery		✓	✓		✓		✓	✓	✓	
Hazardous waste disposed		✓	✓		✓		✓	✓	✓	
TECHNICAL INDICATORS										
INPUT										
Quantity of primary materials used	✓	✓	✓		✓	✓	✓	✓	✓	
Quantity of secondary materials from reuse	*	*	*		*	✓	*	*	*	
Quantity of secondary materials from recycling	*	*	*		*	✓	*	*	*	
Quantity renewable materials used										
Quantity of scarce materials used	✓					✓				✓
Utility of a product						✓				
Disassembly factors										
Toxicity		✓				✓				✓
OUTPUT										
Quantity of materials for reuse		✓	✓		✓	✓	✓	✓	✓	
Quantity of materials for recycling	✓	✓	✓		✓	✓	✓	✓	✓	
Quantity of materials sent to landfill		✓	✓		✓	✓	✓	✓	✓	
Efficiency of the recycling process										
Quantity of waste generated in the recycling process										

4.2.3. Chapter Summary

In this chapter relevant scholar works related to Material Passports and Banks were presented. It became clear that nevertheless the concept is not new, up until now there is no common definition or structure for Material Passport in use. However, the analyzed publications authors agree that MP is a key element for Circular Economy implementation in built environment. Currently there are various propositions related to the structure and contents of MP. It was identified that most of the propositions, no matter how extensive, concentrate mostly on sustainability factors and lacks technical properties, which are crucial for building material and component reuse. Furthermore, MP were introduced in context of the building's life cycle, based on which the scope of the project was reduced to Conceptual Design and Preliminary Design stages. Additionally, while analyzing the challenges imposed for Material Passport implementation it became evident that the process is complex and require contribution from various stakeholders addressing many regulative, management and technical aspects. However, in relation to the scope of this thesis authors have stated that only the technical aspects will be addressed during this study.

Similarly, to Material Passports the idea of Buildings as Material Banks is not new as well, but the concept came to life quite recently with EU Horizon project BAMB. The contributions for material banks were introduced based on both research on relevant publications as well as databases found on-line. From the publication side, a BIM-based database tendency is seen as the authors suggest many frameworks to generate Material Passports while supplementing BIM data with CE relevant data from external sources. Some authors even propose storing the data inside BIM models, however there are counterarguments saying that this kind of approach would make the model redundant and data not easily accessible for different stakeholders. In contrast, was identified that currently there are many databases around the World proposing necessary sustainability information for building materials and components. Nevertheless, there is no common structure, the data that databases hold differ seemingly, big part of them are not publicly accessible or require a license, the formats databases are presented in vary from web-based to Excel formats, some databases hold information relevant only for specific regions, the extensiveness diverge from a couple of hundreds of materials/products to thousands and even in the same database different materials/products can hold not the same amount of information.

To look deeper into the contents of most relevant and used material databases in relation to Circular Economy a comparison matrix was introduced (Table 9). The databases were studied in relation to the accessibility as well as sustainability indicators and technical indicators they hold. It is easy to see that none of the databases hold all of the information listed and most importantly technical indicators are covered very poorly. For example, disassembly factors crucial for *Design for Deconstruction* strategy are not present anywhere. As well as *Utility of a product* factor indicating the lifespan of the component is proposed only in BAMB database which is still under development. Looking further into the technical output factors it is also evident that none of the databases cover the *Efficiency of recycling process* or *Quantity of waste generated in the recycling process*.

Table 10 gives a short overview of the scholar works included identifying the authors, year of publication and key takeaways.

Table 10: Authors and their contributions included in the literature review for chapter "Material Passports and Banks"

Author	Year	Contribution to Material Passport definition/contents and MP database development
Maayke Aimée Damen	2012	Defined the concept and format of resources passport for Circular Economy addressing resources scarcity, including the roles and information needs of different actors, governmental policies, management aspects. Identified 11 key information needs out of 25 proposed for a development of a database and resource passport.
R Cossu, ID Williams	2015	Defines Urban Mining and gives a scheme for material flows.
3XN & GXN Innovation	2016	Explained the concept of Material Passport and proposed 5 principles to consider in a MP.
Verberne, J.J.H	2016	Analyzed building circularity indicators and proposed circular bill of materials (BOM) structure, which included key indicators necessary for Design for Disassembly (DfD).
R.J. Geldermans	2016	Distinguished Intrinsic and Relational properties of materials and proposed 7 data categories to consider addressing circularity potential.

Lars Marten Luscuere	2017	Explored the need of Material Passports and presented their goals and functions.
Katja Hansen, Michael Braungart, Douglas Mulhal	2018	Defined Material Passports and Nutrient certificates as well as their roles for material recovery in relation to building layers.
Eline Leising, Jaco Quist, Nancy Bocken	2018	Includes buildings as material banks in Circular Economy definition for built environment.
Lars Luscuere, Douglas Mulhall	2018	Explored the history of Material Passport concept and introduced the proposition from project BAMB, identifying key stakeholder inputs for MP database and characteristics M should carry.
B Gepts, E Meex, E Nuyts, E Knapen and G Verbeeck	2019	Proposed a framework for combining two databases in order to show the potential of existing building as material banks.
M Honic, I Kovacic and H Rechberger	2019a	Defined BIM-based material passport and the scope of it throughout the life cycle of a building based on 4 building levels.
Meliha Honic, Iva Kovacic, Helmut Rechberger	2019b	Identified a gap for BIM supported MP passport generating tool and proposed a system architecture to fill this gap employing 2 external databases.
Meliha Honic, Iva Kovacic, Goran Sibenik, Helmut Rechberger	2019c	Proposed a BIM-based tool for MP generation employing an external database and a Material Inventory and Analysis tool for creating predefined passport properties. As well introduced a data and stakeholder management framework for BIM-based MP implementation.
Meliha Honic, Iva Kovacic, Helmut Rechberger	2019d	Analyzed recycling potential of buildings with support of Material Passports and proposed a system architecture for another BIM-based MP generation while storing the data in MS Excel format.
M R Munaro, A C Fischer, N C Azevedo, S F Tavares	2019	Identified the lack of performance properties in currently existing environmental declarations and proposed a structure for MP with 8 main sections including one for disassembly guidance.
Matthias Heinrich, Werner Lang	2019	Analyzed best practices for material passports and outlined a material data tree for Circular Economy (Project BAMB publication).
Gaochuang Cai, Danièle Waldmann	2019	Defined main businesses of material and component bank as well as its' role during the whole life cycle of a building.
Felix Heisel, Sabine Rau-Oberhuber	2020	Defined Material Passport and introduced a structure generated by Madaster platform in a case study of a fully circular residential unit UMAR.
Laddu Bhagya Jayasinghe, Daniele Waldmann	2020	Proposed a framework for a BIM-based Web tool as Material and component bank employing Dynamo visual programming tool and MYSQL database. Defined the information database should hold grouping it in 9 sections.
Ingrid Bertin, Romain Mesnil, Jean-Marc Jaeger, Adélaïde Feraille, Robert Le Roy	2020	Developed a Microsoft SQL Material Bank for load-bearing constructions and tested for two scenarios: "design from a stock" and "design with stock".
Amjad Almusaed, Asaad Almssad, Raad Z. Homod, Ibrahim Yitmen	2020	Analyzed existing propositions of Building Material Passports in order to introduce a MP needed in hot climates.
Ioana Miu	2020	Analyzed the concept of Material Passport, history, definitions, and peer contributions, finally proposing a structure for standardized MP.

4.3. Semantic Web and Linked Open Data

In this chapter Semantic Web (SW) and Linked Open Data (LOD) are presented in relation to solving fragmented and scattered data management issues between AEC industry and product manufacturers. While further the related works are analyzed in relation to previously identified technical circularity indicators. This chapter answers the last part of the problem formulation sub-question two (SQ2). *Web of Science* and *SCOPUS* were screened in order to identify relevant contributions for *Semantic Web and Linked Open Data* in relation to manufacturer product and building product data including the synonyms of concepts (Table 11).

As the research area of Semantic Web and Linked Open Data is very broad and results in tens of thousands results alone it had to be narrowed down to feasible number of hits for review regarding the extents of this thesis. Therefore, the concept of SW and LOD was combined with manufacturer product data and building product data. A joined query from the synonyms stated in Table 11 resulted in 33 hits in *Web of Science* and 63 hits in *SCOPUS*. Following the *PRISMA framework* (Moher et al., 2009) finally 13 studies were chosen for qualitative analysis while 6 more added during the snowballing process of final set of papers (Figure 20).

Interesting observation was found when trying to combine SW and LOD query with "material passport" or "material bank" as there were no results either in *Web of Science* or *SCOPUS*. As well when SW and LOD query was combined with "Circular Economy" only 2-3 hits showed up in each database. Therefore, as showed in Table 11 Circular Economy concept was expanded to related concepts like sustainability or waste management.

As in previous chapter a complimentary Snowballing research in *Google Scholar* databases was executed. (Wohlin, 2014). A *Snowballing Protocol* for this part of research was created and can be seen in Table 12. During two backward and forward iterations a total of 30 papers out of 46 fully reviewed were included to final literature review of this chapter. The inclusion and exclusion criteria were set the same both for the *PRISMA framework* and complimentary *Snowballing* research. Finally, the results of both research approaches were compared, and 13 duplicates excluded resulting in last set of 28 papers included in this chapter's literature review.

Table 11: SW and LOD search concepts and synonyms

Search concept	Synonyms
Semantic Web and Liked Open Data	{"semantic web" OR "resource description framework" OR "liked building data" OR "linked open data"}
Manufacturer product data and building product data	{"manufacturer data" OR "material data" OR "product data" OR "product manufacturer data" OR "manufacturer product data" OR "building product*"}
Circular Economy	{"sustainability" OR "waste management" OR "Life Cycle Assessment" OR "Circular Economy"}

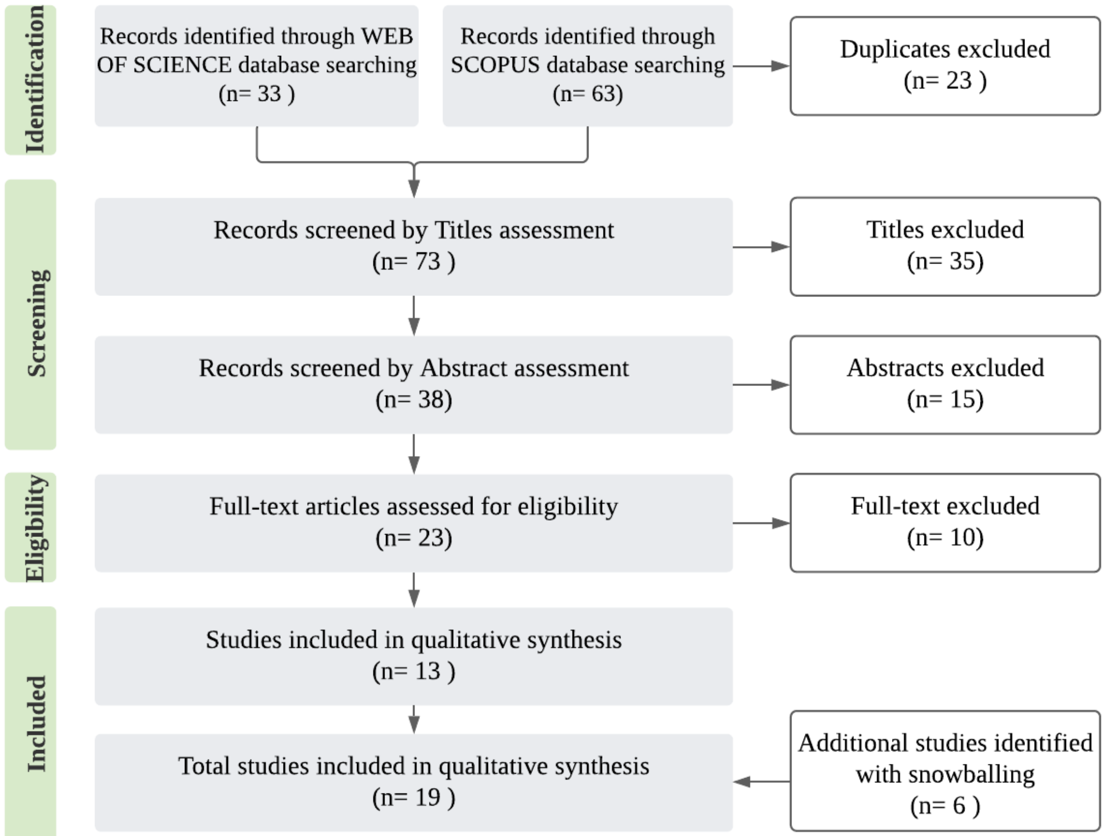


Figure 20: PRISMA framework diagram showing paper selection process

Table 12: Snowballing protocol for Data management in AEC industry research

SNOWBLLING PROTOCOL	**SUBQUESTION SQ2**			
	Research content	Data management in AEC industry		
	Breakdown	Semantic Web and Liked Open Data	Manufacturer product data and building product data	Circular Economy
	Keywords	Semantic Web, Linked Data, Web Ontology Language (OWL), Resource Description Framework (RDF), Ontologies, material ontology, manufacturing process ontology, manufacturing ontologies, Open data, Semantic data-model.	Building Information Modelling (BIM), Building materials database, Data integration, Intelligent manufacturing, digital manufacturing, product description.	Building waste analysis, Construction waste minimization, Circular Economy, Sustainability analysis, Life Cycle Assessment.

	Search strings	{"semantic web" OR "linked building data" AND "AEC" OR "built environment" OR "construction"}; {"Resource Description Framework " AND "circular economy"}; {"linked data " AND "circular economy"}; {"semantic web" AND "circular economy"}; {"semantic web" AND "AEC" AND "circular economy"}; {"semantic web" AND "built environment" AND "circular economy"}; {"semantic web" OR "linked building data" AND "AEC" OR "built environment" OR "construction"}; {"RDF" AND "build environment" OR "Construction Industry"}; {"Resource description Framework" AND "Built environment" OR "AEC industry"};		
	Synonyms	Resource Description Framework; Liked Building Data;	Manufacturer data; Material data; Product data; Product manufacturer data; Building product;	Sustainability; Waste management; Life Cycle Assessment;
	Databases and publishers included	Google Scholar; Research Gate; Universiet Gent; SpringerLink; ACM Digital Library;		
	Exclusion criteria	1. Not in English; 2. Published before 2010; 3. Not peer reviewed; 4. Do not contain predefined keywords; 5. Non-scientific work; 6. Full text not available;		
	Inclusion criteria	1. Relevant to AEC industry; 2. Language English; 3. Publication date from 2010 to 2020; 4. Peer reviewed; 5. Contains predefined keywords; 6. Scientific work; 7. Availability full text;		

4.3.1. Industry Data Management Issues and Application of Semantic Web

As it was identified previously currently there are many data sources (databases, certifications, on-line data providers, tools, etc.) offering information relevant to circularity assessment. Nevertheless, it is clear that all the relevant data is scattered among multiple sources and not all information is easily accessible in order to assess the design for circularity. This issue of information systems diversity, lack of large concept libraries as well as the need for data storage in easily accessible and collaborative manner has been addressed for a long time now by many authors (Bilal et al., 2017; Costa & Madrazo, 2015; Liang et al., 2020; Niknam et al., 2019.; Panetto et al., 2012; Pauwels et al., 2017; Vujasinovic, 2020, pp. 230–240). Evidently, there are several factors keeping the AEC industry stagnated towards a common data environment. Most commonly these factors are divided into considerations related to industry itself (complexity, diversity, uniqueness of the projects, etc.), manufacturer (lack of motivation, capabilities, knowledge, etc.) and collaboration/communication between stakeholders (common definitions, standards, ownership issues, etc.) (Godager, 2018; Kebede et al., 2020; Pauwels et al., 2017). Nevertheless, various authors agree that highly specific data is crucial for design assessment at the early stage (Bilal et al., 2017; Costa & Madrazo, 2015; Costa Jutglar, 2017; Kebede et al., 2020).

Presently it is common to store product related data in BIM models or as attached PDFs, however this kind of approach is time consuming, error prone and restricts data accessibility as well as easy retrieval (Costa Jutglar, 2017; Vujasinovic, 2020, pp. 230–240). Semantic Web (SW) technologies and Liked Open Data (LOD) are advocated to flip current practices storing product data in various databases and file formats as PDFs or tabular data as well as to bring a common vocabulary to define information and retrieve it in common data environment (Godager, 2018; Kebede et al., 2020; Pauwels et al., 2017).

"SW and LD technologies enable the sharing of products' information from manufacturers to designers who can search product information, compare different products and take informed design decisions during the very beginning of the design process." (Kebede et al., 2020, p. 248)

The term *Semantic Web* was introduced by Tim Berners-Lee, inventor of World Wide Web and founder of W3C (World Wide Web Consortium) aiming to turn current unstructured Web into a *web of data* (Costa Jutglar, 2017). Resource Description Framework (RDF) is named as a core of the SW, which provides a flexible and generic language to easily represent and combine information from different domains by the use of RDF graphs (Pauwels et al., 2017). Pauwels explains the significance of core SW ontologies namely RDFs and OWL in relation to providing an improved semantic meaning to RDF graphs. On the other hand, Linked Open Data is a part of Semantic Web and was introduced a bit later after realizing that *"quite some data was being published on the web, seemingly following the semantic web idea but actually never linking to outside data, and thus in fact not realizing the initial core idea behind the semantic web, which is linking data",* therefore, to address this issue Berners-Lee introduced four rules for publishing LOD (Pauwels et al., 2017, p. 149). Semantic Web RDF data can be retrieved trough SPARQL queries which is a dedicated query language and W3C recommendation (*SPARQL 1.1 Query Language*, n.d.).

To take advantage of Semantic Web and Linked Open Data technologies in the AEC industry an LBD (Linked Building Data) community group was established as a part of W3C consortium. Among others, linking across domains is named as a main driver behind the initiative (Pauwels et al., 2017).

4.3.2. Ontologies for Manufacturer Data

Ontologies are vocabularies used for data representation and information modelling (Kebede et al., 2020). Costa Jutglar et al. (2017) refers to an ontology as *"a formal and explicit specification of a shared conceptualization of a domain of interest"*, further explaining that here "formal" means that ontology follows agreed rules, "explicit" means that the meanings of relationships are defined explicitly through type, relations and constrains, and "shared conceptualization" refers to a conceptualization between different parties. This ontology definition firstly was introduced by Grubber in 1993.

Currently there are hundreds of ontologies created for various implementations (*Linked Open Vocabularies (LOV)*, n.d.). Manufacturer data ontologies are no exception. Mesmer & Olewnik (2018), Mohd Ali et al. (2020) and Vujasinovic (2020) gives an overview of existing manufacturer data ontologies for various domains:

- DFM- captures manufacturing and assembly concepts, intended to assist the designer to select the best design approach (Chang, 2008).
- FGMO- explicit vocabulary to define functionally graded materials, includes existing applications, manufacturing techniques, and material characteristics (Mohd Ali et al., 2020).
- MSDL- manufacturing service description language, describes conventional manufacturing processes (Ameri & Dutta, 2008).

- FLEXINET- manufacturing reference ontology, captures product-service-production and related concepts; intended for decision making in new product development processes (Palmer et al., 2016).
- MCCO-manufacturing core concepts ontology directed at providing support for product life cycle interoperability between the production and design domains (Usman et al., 2011).
- MASON- manufacturing semantics ontology, built upon three concepts: entities, operations and resources; applied in cost estimation and semantic-aware multiagent system for manufacturing (Lemaignan et al., 2006).
- ManuSquare- ontology for manufacturing information sharing between different stakeholders, defines main concepts like processes, suppliers, products, etc. and related taxonomies for process type, product type, etc. (Landolfi et al., 2018).
- P-PSO- Politecnico di Milano production systems ontology, facilitates the exchange of information about design and control activities (Garetti & Fumagalli, 2012).
- FIF- federated interoperability framework for sustainable product and process data interoperability (Tchoffa et al., 2017).
- MatOnto- ontology for industrial materials, mainly targeted for representing material raw state (Cheung, 2008).
- PMPO- part-focused manufacturing process ontology, targeted for users with limited manufacturing knowledge to be able to identify processes (Mohd Ali et al., 2019).
- ONTO-PDM- product driven ontology for product data management interoperability within manufacturing process environment (Panetto et al., 2012).

However, according to Mohd Ali et al. (2020, p. 3) most of these ontologies are structured in *ad hoc* ways and little effort was spent to reuse them or for creating a global framework.

4.3.3. Ontologies and RDF Material Databases for Building Products

Similarly, to manufacturer data ontologies there are multiple contributions trying to capture the building product data for various purposes. In relation to that some authors proposed new ontologies, some combined or extended existing ones, others even proposed RDF based database structures or search platforms.

One of the earliest and best known works is presented by Costa & Madrazo (2014) named project BAUKOM, aiming to create a comprehensive ecosystem incorporating BIM models and other AEC databases by the use of project specific ontology. Costa Jutglar (2017) showcased the functionalities of BAUKOM including user interfaces for product data specification and rule-checking system aimed for design specific product suggestions. Another contribution for integrating BIM and manufacturer data was presented by Niknam et al. (2018), where the author extended existing BIMSO ontology providing common vocabulary for AEC-FM domains. New extended ontology was called BIMMO and presented more detailed description for BIMSO products. ManuService ontology (Y. Lu et al., 2019) proposed a vocabulary to transform BOM (Bill Of Materials) data to RDF data as well including necessary concepts for description of products in a service oriented business environment. He et al. (2018) introduced an E-Commerce ontology and platform for industrialized construction procurement including six main entities giving a quite detailed product information description. In order to overcome interoperability issues related to product standardization Fraga et al. (2018) suggested an ontology based on ISO standards describing products, processes, resources and enterprises.

While working on project BAUKOM Costa Jutglar (2017) identified existing building product catalogues like BIM Object, Autodesk Seek, Bimetica, etc. While these platforms are intended to increase BIM product reusability and easy retrieval, it was identified that most of these platforms were not capable to represent required geometric and parametric quality for different uses as well as were most often provided in proprietary formats. Addressing interoperability problems for BIM products Gao et al. (2017) introduced BIMTag semantic annotation system and BIMSeek search engine. Recently was proposed more advanced matching algorithm BIMSeek++ for retrieving BIM components using similarity measurement of attributes (Li et al., 2020).

BauDataWeb is a well-known Austrian platform for building and construction material retrieval as Linked Data (Radinger et al., 2013). The system architecture propose integration from various heterogenous data sources like Eurobau or InnData databases which is published as Liked Data and is available through SPRAQL queries. However the tool is no longer maintained and is available only for archiving purposes (*BauDataWeb Query Collection*, n.d.). Another contribution for publishing and accessing building product data named SemCat was introduced by Gudnason and Pauwels (2016). SemCat proposed a tool gathering data from heterogenous sources like production databases, product data templates, PDFs, and BIM tools to a common environment. The first prototype was introduced in Excel format, however there were no following publications found. One more contribution related to semantic material data platforms was created by Liang et al. (2020). Platform named MDSE proposed a Google-like information searching and extraction for multi-source heterogenous material data as XML documents. Among other the platform introduced a functionality to retrieve information from non-textual data sources like images or videos.

Wagner & Ruppel (2019, p. 106) extended SolConPro ontology which was created to describe multi-functional façade elements and introduced the BPO (building product ontology) aimed at *"non-geometric description without defining templates by determination of taxonomies and includes concepts to model assembly structures, interconnections of components, and complex properties and property values"*. Author argues that previously suggested building product ontologies PRODUCT (*W3c-Lbd-Cg/Product*, 2017/2020) and PROPS (Lefrançois, 2017/2020) both holds core issues while defining building products. According to Wagner & Ruppel (2019, pp. 109–110) PRODUCT "*restrains these connections to products alone, therefore every part of a product must be a product itself, which does not hold true in all cases"* and PROPS *"is not aligned towards common vocabularies and does not allow to add further information or meta data to the properties"*. Meanwhile a recent contribution was published by Valluru et al. (2020) presenting an ontology for building material definition named *Digital Construction Building Materials* (DICBM). The ontology makes use of other AEC industry specific ontologies like BOT or OPM. New vocabulary allows to "represent construction and material models of building elements and to improve interoperability"(Karlapudi & Valluru, 2019).

4.3.4. Linked Open Data and Circular Economy

As it was indicated in the chapter introduction, very little research contributions were found related to Semantic Web and Linked Open Data technologies and Circular Economy. Nevertheless, a few of previously mentioned manufacturer data or building product ontologies like MASON, E-Commerce or SMERGY (Shayeganfar et al., 2013) holds some relevant data classes and properties for sustainability, Life Cycle Assessment or Circularity indicators.

A couple of contributions were found related to LCA product data mapping on Semantic Web like IASDOP ontology by Eddy et al. (2013) or a minimal ontology for Life Cycle Assessment Data by

(Janowicz et al., 2015). König et al. (2013) introduced an architecture for open knowledge base for sustainable buildings based on Liked Data technologies. The proposed solution was intended to enable the users to capture, distil, analyze and share building sustainability information among stakeholders.

In *Linked Spatial Data for a Circular Economy (2017*) a Circular Economy ontology was proposed by E. M. Sauter showing a taxonomy divided in two main entities: resources and actors. Sauter et al. (2018) continued his work proposing two corresponding ontologies for Circular Economy namely CEO and CAMO. CEO (Circular Exchange Ontology) is dedicated to describing the elements necessary to execute a material exchange between different actors of CE, while CAMO (Circular Activities and Materials Ontology) provides CE classification system for the different materials, products, and activities. One more ontology for Circular Economy was suggested by Mboli et al. (2020) employing IoT technologies to track and monitor products in real-time. An open source dataset and ontology for product footprinting was introduced with project BONSAI (Ghose et al., 2019). BONSAI is still an ongoing project aiming to build a shared resource basin where components and materials could be shared between community as well supporting LCA calculations. In order to achieve that project authors have employed multiple data sources like Exiobase database or YSTAFDB.

As the research of this thesis is focused on technical circularity indicators for early design assessment, some of the most relevant ontologies described above were examined for existing classes and properties which could define the needed indicators (Table 13).

Table 13: Ontology contents relevant for technical circularity indicators comparison

Information necessary for technical circularity indicators to be defined in ontologies	ONTOLOGY					
	BONSAI	CEO	CAMO	DFM	LCA/LCI (2015)	J.S. Mboli (2020)
Material flows	✓	✓			✓	
Reused/Recycled materials	✓		✓			✓
Renewable materials			✓			✓
Scarce materials						
Utility of a product	✓		✓		✓	✓
Disassembly			✓	✓		
Toxicity						
Waste		✓				✓

4.3.5. Chapter Summary

During the literature review of this chapter, we have identified the current data management issues relevant to circularity assessment which highly relies on large amount of heterogenous data scattered across different domains, platforms and file formats. It was revealed that various scholars are suggesting Sematic Web and Linked Open Data technologies in order to create a common data environment where information from different sources could be stored in a structured way and easily retrievable in an open platform. Therefore, a short introduction to SW, LOD and related entities were given including the initiatives relevant to AEC industry.

For the purpose of this thesis was necessary to look deeper into proposed vocabularies or ontologies describing manufacturer data and processes, building products and current initiatives to combine this data. Therefore, firstly an overview of most referred ontologies describing manufacturer data was given. While analyzing each of them it is clear that so far these ontologies mostly concern about the processes and information flow and just a few looks with more detail into manufacturer data related to the product itself.

Further research revealed a few ontologies designed specifically for describing building products. As the need for a common platform manufacturer data and BIM data was highly emphasized by many scholars, some of them took the initiative and proposed ontologies or common frameworks to achieve this combination. However, none of these platforms are currently functioning or providing open access to developed tools.

Finally, the contributions related to Semantic Web technologies and Circular Economy were identified. As it was already clear from the chapter introduction, currently there are not many scholars works related to both CE and SW. Nevertheless, a few contributions were identified related to CE concept or similar concepts as sustainability, Life Cycle Assessment, or waste management. Under a closer look these ontologies were overviewed looking for relevant classes and propertied defined in their vocabularies relevant to technical circularity indicators and presented in Table 13.

In conclusion, this chapter's literature review revealed that currently there are many ontologies describing product and manufacturer data separately for various applications. Some ontologies are even specifically created to describe building products or made to combined data from both domains in order to give better parametric descriptions. However, in relation to this thesis, there are two main issues observed. Firstly, most of the ontologies are created in *ad hoc* ways and none of them represents a full structure for data necessary in order to assess technical circularity aspects. Secondly, none of the revived ontologies provided all the classes and properties needed to describe technical circularity indicators.

Table 14 gives an overview of the most relevant scholar works identified during this review related to representation of manufacturer product and BIM data as well as if the sustainability, LCA, waste management or CE factors was reflected in their work.

Table 14: Overview of most relevant scholar works identified in this chapter

Author (Project)	**Year**	**Proposed a new ontology for product data representation or a new structure from existing ontologies**	**Combined manufacturer data and BIM data**	**Proposed RDF based database and/or search platform for manufacturer data**	**Addressed sustainability, LCA, waste management or CE**	**Proposed a supporting APP or tool**
Andreas Radinger, Bene Rodriguez-Castro, Alex Stolz, and Martin Hepp	2013			BauDataWeb		+
G. Costa, L. Madrazo (BAUKOM)	2014	BAUKOM	+	+		+

Bo Yan, Yingjie Hu, Brandon Kuczenski, Krzysztof Janowicz, Andrea Ballatore, Adila A. Krisnadhi, Yiting Ju, Pascal Hitzler, Sangwon Suh, Wesley Ingwersen	2015	+			+	
G. Gudnason, P. Pauwels	2016		+	SemCat	+	+
Ge Gao, Yu-Shen Liu, Pengpeng Lin, Meng Wang, Ming Gu a, Jun-Hai Yong	2017	BIM Tag		BIM Seek (From 2020 BIM Seek++)		+
Muhammad Bilal, Lukumon O. Oyedele, Kamran Munir, Saheed O. Ajayi, Olugbenga O. Akinade, Hakeem A. Owolabi, Hafiz A. Alaka	2017	+		+	+	
Elke M. Sauter, Martijn Witjes	2017	Circular Economy Ontology			+	
Giuseppe Landolfi, Andrea Barni, Gabriele Izzo, Elias Montini, Andrea Bettoni, Marko Vujasinovic, Alessio Gugliotta	2018	MANU-SQUARE		MANU-SQUARE	+	
Dandan He, Zhongfu Li, Chunlin Wu, Xin Ning	2018	+	+	E-Commerce	+	
Mehrdad Niknam, Farzad Jalaei, Saeed Karshenas	2019	BIMMO	+			
Elke Sauter, Rob Lemmens and Pieter Pauwels	2019	CEO & CAMO		+	+	+
Julius Sechang Mboli, Dhavalkumar Thakker, Jyoti L. Mishra	2020	+			+	
Emil Riis Hansen, Matteo Lissandrini, Agneta Ghose, Søren Løkke, Christian Thomsen, and Katja Hose	2020	BONSAI		+	+	+

4.4. Identifying the gaps

The performed desk research related to existing circularity assessment models, indicators, Material Passports, and databases showed a number of gaps currently preventing Circular Economy implementation in AEC industry. In this sub-chapter the main identified gaps are listed to be addressed in the following chapter *"Towards Open Data Platform for Circularity assessment"*.

BIM environment gaps

- IFC data model lacks structure to capture CE principles.
- Use of application-programming interface (API) to integrate with the BIM tools limits the interoperability.

Assessment gaps

- Circular buildings design aspects are not fully covered.
- Disassembly of buildings and their components at the end of their life phase is not commonly considered during the design.
- Lack of legislation to implement DFD in the design.

Circularity assessment tool gaps

- Reliance on IFC and tabular data as input.
- Reliance on BIM proprietary tools to conduct the assessments.
- Assessment not detailed enough for DfD.

Material Passport gaps

- No common definition or structure.
- Current MP propositions lacks technical properties like disassembly factors, which are crucial for circularity assessment.

Existing databases gaps

- No common structure.
- Some DB provided in closed environments, leading to accessibility issues.
- No common format. Formats databases are presented in various formats from web-based to Excel formats.
- Geographical limitations. Some databases hold information relevant only for specific regions.
- Extensiveness divergence. Identified databases holds from a couple of hundreds of materials/products to thousands and even in the same database different materials/products hold not the same amount of information.

Data management gaps in AEC industry

- Large amount of heterogenous data scattered across different domains, platforms, and file formats.
- No common data environment where information from different sources could be stored in a structured way and easily retrievable in an open platform.
- No currently functioning open platform for integration of manufacturer data with BIM model data.
- No vocabulary that represents a full structure for data necessary in order to assess technical circularity aspects.

5. Towards Open Data Platform for Building's circularity assessment

This chapter is dedicated to answer the third sub-question of the problem formulation. The desk research results are analyzed together with the inputs retrieved from the interviews with industry professionals. Based on the analysis results the research gaps to be addressed further are distinguished, system requirements formulated, and user stories drawn. Subsequently, circularity assessment models are analyzed and final model to be used in this study presented. Next, an analysis on the existing manufacturer data sources and existing ontologies is drawn in relation to the selected assessment model. Finally, a conceptual definition for a new BCAO ontology is proposed and a final concept for circularity assessment system framework is given.

5.1. Interviews with industry

In order to confirm the desk research results and get professional insights on developed solution four semi-formal interviews were conducted. Interviewees were picked based on intentional sampling with the purpose of collecting the data from three types of stakeholders namely an architect, manufacturer, and project manager. Three interviewees were picked from Denmark and one from Netherlands. All of the participants have from 10 to 16 years of experience in the field and takes managing positions. The analysis of the interviews was done following the seven steps presented in "*2.4 Methods*" subchapter.

The authors of the thesis are fully aware that the number of interviews conducted is not sufficient to represent any generalizations about the industry. However, the goal of these interviews was to confirm the hypotheses derived from desk research and assist to derive requirements for the system framework. Therefore, the questions for the interviews were composed accordingly and supported by authors identified in literature review (Table 15).

Table 15: Interview questions and hypotheses from literature review

Source	Hypothesis	Interview question
General knowledge		
(Gallego-Schmid et al., 2020; Mayara Regina Munaro et al., 2020; Ness & Xing, 2017; Pomponi & Moncaster, 2017)	Circular Economy concept in AEC industry is still in its infancy.	What do you know about the Circular Economy concept?
Design strategies and early project design		
-(Kanters, 2020) -(Go et al., 2015; Moreno et al., 2016; Sassanelli et al., 2020). - Akinade et al. (2017)	-Lack in the coverage of circular buildings design aspects. -Different circular design strategies can have positive contribution related to sustainability and CE implementation in the AEC industry -legislation and building certification systems lack consideration for circular building design	Do you use any design strategies (Design for Disassembly, Design for Adaptability, C2C, etc.) /certifications (DGNB, EPD, ISO, LEED, BREEM, etc.) related to sustainability or circular economy in your work? Which ones and what are the reasons?
(Tingley and Davison, 2011)	-Lack of information related to existing buildings - Communication is a key for designers to acquire information related to the products composition and material.	How much material information is available when starting the design process?

(M Honic et al., 2019; L. Luscuere, 2018; M R Munaro et al., 2019)	Current Material Passports and existing certificates like Environmental Product Declaration (EPD), Material Safety Datasheets (MSDS), quality declarations, security measures, lists of material and substances or performance properties lacks information supporting resource productivity.	Have you heard about the concept of Material Passport? Is it used in your company or by company partners? Do you see any benefits/drawbacks of it?
(Bilal et al., 2017; Costa & Madrazo, 2015; Landolfi et al., 2018; Liang et al., 2020; Niknam et al., 2019; Panetto et al., 2012; Pauwels et al., 2017; Vujasinovic, 2020, pp. 230–240)	Material data is heterogenous and scattered between multiple resources in various formats like tabular data or PDFs.	What kind of material data do you have access to? Is it directly from manufacturers or external databases? In what format you can retrieve that data? Do you have access to additional data if you need to?
-(Kanters, 2018,2020) - (Durmisevic Elma, 2006) - (EMF, 2013)	- Disassembly of buildings and their components at the end of their life phase is not commonly considered at the design level - DFD is the core for circular building design. -Construction and demolition materials waste are not being exploited for further use -The extent of material recovered at their end-of-life phase are much lower than the extent of virgin material consumption	Are you familiar with design for disassembly concept and do you take in consideration the reusability of material at building end of life?
Data handling		
(Costa Jutglar, 2017; Vujasinovic, 2020, pp. 230–240)	Presently it is common to store product related data in BIM models or as attached PDFs.	How do you store and share the material data within the company and partners? Do you see any issues in the current ways? What could be different?
(Godager, 2018; Kebede et al., 2020; Pauwels et al., 2017)	Semantic Web (SW) technologies are advocated to flip current practices storing product data in various databases and file formats as PDFs or tabular data as well as to bring a common vocabulary to define information and retrieve it in common data environment.	Imagine there would be an open linked database carrying material passports and other circularity assessment related information collected from various stakeholders like designers, manufacturers, governmental institutions, etc. Do you see any benefits or drawbacks this kind of technology might bring? Would you find it useful and how?
Design assessment		
-(Cambier et al., 2020) -(Röck et al., 2018)	- Many assessment models and tools have been developed to support the AEC industry in its transition from linear to circular model - It is beneficial to conduct the assessment practices at early design stage	Do you know any assessment frameworks/tools related to sustainability or circular economy applied to the preliminary design? Do you use any of those in your work? What encourages/prevents you from using them?

5.1.1. Interviews analysis

The interviews showed that all four interviewees were well informed about the concept of Circular Economy and had some related experience in their workplace. However, it is worth to mention that all of the interview participants were personally interested in the mater, therefore had some additional education in that regard or have been working on supplementary related projects. Still, they have confirmed that CE in AEC industry is still in its infancy as there are just a few pilot projects initiated in several countries. All of the interviewees have mentioned standardization and legislations as driving factors and the fact that it is still a lack of them stagnates the process. As well the absence of initiative from owner/client part is commonly mentioned and slow industry participation is advocated on behalf of meeting the market needs.

Regarding the standardizations the interviewees were asked about what type of sustainability or Circular Economy related standards or design strategies they use in their work. EPDs (Environmental Product Declarations) were mentioned the most, three out of four interviewees claimed that they have been using EPDs for work purposes. However, there were several drawbacks indicated on the standard itself. For example, *Interviewee B* mentioned that the standard is not extensive enough as more information about maintenance or elements' lifespan could be added. Furthermore, *Interviewee C* explained that EPDs vary as well depending on the country or specific manufacturing processes even while speaking about the same product. LEED standard was mentioned by two interviewees both from Denmark and Netherlands. DGNB standard was indicated to be the most used in Denmark compared to other sustainability standards. However, according to *Interviewee D*, the standard itself is not very useful for environmental purposes as based on him it brings very minimal actual change in projects and works more for the sails process: *"The builders tend to chase for certification points that cost the less which shows a good score but do not really make the building much more sustainable"*. Similar tendency also noticed by *Interviewee A* speaking about LEED certificates arguing that companies are trying hard just to get the certificate in order to show that *"they are environmental"*.

Concerning the design strategies only Design for Deconstruction/Disassembly was discussed. Three out of four interviewees were aware of DfD. However, all of them confirmed that the strategy is not implemented anywhere in their workplace. Only *Interviewee C* was involved in a pilot project while building a fully circular house in Denmark where all the parts were intended to be reused for the second life. According to *Interviewee D* Design for Disassembly is driven by the architect or project manager itself. From his own perspective he often tries to incorporate elements that are compliant with DfD, however he has faced some barriers indicating engineering part of the project as one of the most common.

In order to be able to assess the early design it is important to know how much of necessary information is available at the early stages of the project. Only two interviewees were able to answer this question from a designer perspective as *Interviewee A* as a project manager has never been involved in a design process in such detail and *Interviewee C* is mainly specifying in element connection parts design, therefore his answers was more valuable as from manufacturer side. Nevertheless, *Interviewees B and D* have been involved in the design itself and have revealed that currently there are many issues with the data available for design assessment. First of all, many different sources like manufacturer websites, EPDs, external databases, LCA tools or internal data storage was uncovered. This shows that there are data sources available, but they are scattered among various platforms. Furthermore, the data is structured in many different ways and is provided in diverse formats like Excel spreadsheets, PDFs or sometimes closed in some specific software. That being said, it makes it hard for a designer to connect all the required data for one project as well as raises questions about information reliability. *Interviewee D* while working on some related projects have noticed a big difference in the data provided in manufacturer website compared to data in LCAbyg for example.

Material passports in the literature are referred as the means to provide structure for material/product data. Three out of four interviewees were aware about the MP and have been using them in one form or another. As EPD can also be considered as material passport *Interviewee C* indicated that the company, he works in provides MP as EPDs. *Interviewees B and D* are also using some formats of MP. However, it became clear that currently there is no common structure available and the need for it was expressed by both interviewees. Still, the interview participants have referred to some company specific practices to provide the data about products. *Interviewee D* have even specified sustainability measures that are taken in consideration in priority order namely CO_2 emissions, amount of reused or recycled materials embedded in the products and if they can be reused or recycled at the end of buildings' life. He explained that these measures are mostly used because they are the easiest to understand for the client.

Going a bit deeper into the circularity assessment itself it was important to know if the factor of element reusability comes into consideration while designing a new project. Therefore, the DfD design strategy was explored in more detail. As it was mentioned before three out of four interviewees were familiar with the concept. Nevertheless, different approaches could be recognized. For instance, *Interviewee C* has indicated that the company is not only concentrating on assembly parts to be easily deconstructable, but also trying to optimize them by reducing the size of construction part while keeping the same technical requirements. This as well leads to savings in materials for a single element. However, other interviewees indicated that reusability as a part of DfD strategy is rarely considered in today's projects.

Subsequent cluster of interview questions was directed to internal company practices for data storage and sharing among the stakeholders. Here once again a lot of different ways and formats were mentioned even among one company. *Interviewee B* mentioned data storage and sharing in formats like IFC, REVIT models and written documentation like Excel, Word, or PDF formats. *Interviewee C* said that the company uses *ProdLib* software for internal data storage. While *Interviewee D* have revealed even more ways like internal file folder based digital archive for EPDs in saved as PDFs; Data storage within LCAbyg software, connected to Oekobaudat and Sustainability Sheets from Green Council; Storage in BIM models and as exported in Excel format, etc. However, when looking at all of these approaches it become clear that even at the same company there is no common way to collect all relevant data in one accessible place. That being said, it brings a lot of subsequent issues as for instance lack of means to update the information easily if it is stored as a PDF. As well as assessment mistakes by manually typing the data and converting the units as explained by *Interviewee D*. *Interviewees B and D* have mentioned own initiatives for creating this type of platform internally, though they have encountered barriers which mostly comes back to the lack of standardization for common data structuring.

At this point of the interview the idea for an open linked data platform developed in this thesis is introduced and the interviewees were asked if they would find this type of solution useful as well as what issues can they predict. All interviewees agreed that this type of platform would benefit the Circular Economy implementation and help the assessment. However, some considerations were expressed. *Interviewee A* reflected on limitations regarding necessity to enter data in harmonized way, ensure quality control and terminology coherence. *Interviewee B* pointed out to a huge effort needed to collect material data due to its' unstructured nature. *Interviewee C* expressed considerations about data privacy and once again pointed to the need for standardization and legislations. While *Interviewee D* looked further into the future finding additional value for this kind of storage when presently developed technologies will be available.

Finally, the last question was dedicated to reflecting on the assessment itself as well as the tools and practices used for that purpose. Unfortunately, none of the interviewees could give an example of circularity assessment in their work experience, thus was mentioned that it was discussed within the company. *Interviewee B* indicated lack of initiative from clients who are normally concentrated on lowest costs and fastest establishment as one of the main barriers. The only type of assessment to be implemented in practice was mentioned by *Interviewee D* which is LCA assessment. For LCA assessment tools like LCAbyg or One Click LCA was mentioned. The overview of the interviews and more explicit data gathered can be seen in Table 16.

Table 16: Industry interviews overview

	INTERVIEWEE			
	A	**B**	**C**	**D**
Experience in the industry	16 years of experience in various roles such as consulting, business development and specialist project manager. Background in earth science, now the executive director of an earth science matters foundation.	Head of digital innovation at a large construction consultancy company in Denmark. More than 15 years of experience in the industry.	Managing director (who is also a civil engineer) of a large international company providing a wide range of assembly details for concrete structures and composite beams located in Denmark. Experience in the company for almost 15 years.	Architect for 10 years. Current role project architect and project manager. Took the course to qualify as DGNB consultant, as well different LCA and LCC (Life Cycle Costing) courses.
Knowledge about Circular Economy	Have good understanding, have participated in related projects.	Have good understanding, have participated in related projects.	Have good understanding, have participated in related projects.	Have good understanding, have participated in related projects.
Mentioned design strategies/certifications	LEED	EPD, LEED, DGNB, DfD	EPD, DfD	DfD, DGNB, EPD
Material information availability at early design stage	Not sure.	Information available in scattered data sources.	Company itself is assembly parts manufacturer	Information available in scattered data sources.
Knowledge about Material Passports	Do not have any insights.	Aware of the concept. Indicates the need for widely used structure.	Use in a structure of EPD.	Aware of the concept. Company itself do not have internal structure, however sustainability measures prioritized internally as following: CO2 emissions, amount of reused or recycled materials embedded in the products and if they can be reused or recycled at the end of buildings' life.
Type and sources of available material data at the early design stage	Not connected with the design process.	Scattered data from external databases, EPDs, internally collected data in Excel or PDF.	Did not specify.	Scattered data from external databases, EPDs, manufacturer websites, internally collected data in Excel or PDF.

Material reusability consideration at the early design stage	Not connected with the design process.	Familiar with DfD concept, however not implementing in the workplace.	Fully cognizant about DfD. Provides assembly parts and other construction components like beams compliant with the concept.	DfD is driven by the architect himself or a project manager. Personally, in his work considers it, but it is not a common practice.
Practices for sharing and storing circularity and sustainability related data within the workplace and external stakeholders	Has no knowledge how it is stored.	Various formats like IFC, REVIT models and written documentation like Excel, Word, or PDF formats. Internal data handling structures.	Internal component data storage. Uses ProdLib software.	Internal file folder based digital archive for EPDs in PDF. Data storage within LCAbyg software, connected to Oekobaudat and Sustainability sheets from Green Council. Stored in BIM models, exported in Excel format. Internal product templates and assemblies. Making their own tools and software.
Issues related to internal data storage	Has limited material data information.	No common standard for data handling, which leads to failure of most initiatives.	Closed environment, this data is not easily accessible for other stakeholders.	EPDs need to be updated, has limited time to be valid. Internal file-based archives not used as much for data retrieval, normally would just look at the manufacturer website. Rarely all necessary information provided in LCAbyg, have to build the information manually. Brings big risk of failure due to typing mistakes and unit translations. Information not reliable. Exported Excel documents from BIM becomes "dead£ spreadsheets. Internal templates cannot be extensive enough due to variety of projects.
Reflections on Open Linked Database solution	Positive view. Sees limitations regarding necessity to enter data in harmonized way, ensure quality control, terminology coherence.	Information should be stored in an open, machine readable format which is not fixed to a specific software. Points to a huge effort needed to collect material data because it is unstructured.	Open Linked Database would speed up the CE implementation process. Has considerations about data privacy. Expressed the need for standardization and legislations.	Finds it useful especially in relation to carry the data in a platform that is time resilient. Points out to the additional value this kind of storage could gain in the future when presently developed technologies will be available.
Early design assessment for circularity: tools and practices	Not involved in this type of assessment.	Not done in the company he is currently working, however has been discussed. Lack of initiative from clients, normally concentrated on lowest costs and fastest establishment.	Not done.	Use LCAbyg for LCA assessment, tried One Click LCA but have dropped. Also use *Material Pyramid* for CO2 emissions and LCA criteria assessment.

5.2. Desk research and interview results comparative analysis

The interviews analysis offered some insights into the impediments and opportunities with respect to circularity assessment in a more practical context. Assessing both the interviews and the research gaps identified through the literature review can link the bridge between theory and practice. As mentioned before the specimen of the interviewee was not exhaustive. Yet, it helped the purpose of this study. Nevertheless, this section is concerned with comparing the interviews findings with the research gaps identified in the literature, in order to steer the focus towards the most important limitations and further analysis.

To begin with, the circular design strategies. It can be inferred from the reviewed literature that design aspects related to materials and products circularity in terms of reducing waste by repurposing or upcycling are not widely adopted. For instance, design for disassembly aspects proved to enhance the degree of building elements reusability and reduce demolition waste. However, few buildings were designed taking DFD in consideration. One of the main reasons for this phenomenon is the lack of legislation from governments and consideration for those aspects in sustainable building certifications. To compare those gaps with the interview's findings, it can be noticed that circular design strategies such as DFD aspects were recognized and use benefits were acknowledged in such way of reusing the building elements at their EOL. Similarly, optimizing building elements by reducing the materials used without jeopardizing its integrity. However, circular design strategies were not widely adopted in construction projects.

In relation with the circularity assessment models and tools. Literature revealed that there are few studies covering the topic of building circularity. Additionally, BIM-based circularity assessment tools fall short in various aspects. For example, different tools were developed using several BIM authoring tools. In addition of developing various plug-ins utilizing different APIs for the purpose of the assessment. This creates an interoperability issues for data exchange and difficulties in the use of specific plugins. Moreover, IFC open standards lacks the capacity to capture data related to CE. Generally, the interviews, reflected the participants lacks knowledge in relation to building circularity assessment models and tools. Claiming that such practices must be driven by clients and further explain that clients are more oriented towards financial aspects.

Moreover, the literature revealed various limitations with respect to data management in the AEC industry. Illustrating the difficulties to aggregate the significant amount of scattered data related to different domains. Lack of common data environment to store and retrieve information in structured way. Meanwhile, the interview participants emphasized on the importance on the availability of information specially at early design phase. additionally, issues regarding the availability of design assessment related data were mentioned. Conforming to the matter of availability of data in an unorganized manner and which is scattered amongst many different platforms and diverse formats. As a result, discrepancies between the same sets of data can be identified.

Accordingly, research gaps identified in the literature associated with databases and material passports described the lack of common approach to structure the data. The absence of technical properties in relation with materials and products circularity and geographical limitations in connection with the data distinctiveness for each region. Additionally, the absence of vocabulary that represents a full structure for data necessary in order to assess technical circularity aspects. On the other hand, the interviews described that even in the same company there are various approaches to store and access data, which in return requires more effort to update data stored in various methods and different formats increasing the chance of error. Subsequently, the interviewee supported the concept of an open linked data platform to facilitate building circularity assessment. Table 17 offers a summary of both research gaps identified in the literature and the corresponding interviewee mentioned or affirmed those gaps.

Table 17: Identified gaps by desk research in reflection to interview results

Literature Gaps	Interviewee			
	A	B	C	D
BIM environment gaps				
•IFC data model lacks structure to capture CE principles.				
•Use of application-programming interface (API) to integrate with the BIM tools limits the interoperability.				
Assessment gaps				
• Circular buildings design aspects are not fully covered.		✓	✓	✓
•Disassembly of buildings and their components at the end of their life phase is not commonly considered during the design.		✓	✓	✓
•Lack of legislation to implement DFD in the design.		✓	✓	✓
Circularity assessment tool gaps				
•Reliance on IFC and tabular data as input.				
•Reliance on BIM proprietary tools to conduct the assessments.				
•Assessment not detailed enough for DfD.				
Material Passport gaps				
•No common definition or structure.		✓	✓	✓
•Current MP propositions lacks technical properties like disassembly factors, which are crucial for circularity assessment.			✓	
Existing databases gaps				
•No common structure.		✓	✓	✓
•Some DB provided in closed environments, leading to accessibility issues.			✓	✓
•No common format. Formats databases are presented in vary from web-based to Excel formats.		✓	✓	✓
•Geographical limitations. Some databases hold information relevant only for specific regions.			✓	
•Extensiveness divergence. Identified databases holds from a couple of hundreds of materials/products to thousands and even in the same database different materials/products hold not the same amount of information.	✓	✓	✓	✓
Data management gaps in AEC industry				
•Large amount of heterogenous data scattered across different domains, platforms, and file formats.	✓	✓	✓	✓
•No common data environment where information from different sources could be stored in a structured way and easily retrievable in an open platform.	✓	✓	✓	✓
•No currently functioning open platform for integration of manufacturer data with BIM data.				
•No vocabulary that represents a full structure for data necessary in order to assess technical circularity aspects.	✓	✓	✓	✓

Gaps colored in black in Table 17 are excluded and will not be analyzed further. The gaps and exclusion criteria are described as per the following:

Assessment gaps and Circularity assessment tool gaps

- *IFC data model lacks structure to capture CE principles and reliance on IFC as input:* It was decided to exclude this point for further analysis as this study focus is not to suggest a modification for IFC data model by extending its schema to capture CE related data. But instead to propose linked open data technology as it can bridge this gap by providing a vocabulary to capture data related to circulatory assessment

Material Passport gaps and Existing databases gaps

- *Use of application-programming interface (API) to integrate with the BIM tools limits the interoperability:* The scope of this research does not cover the implementation of different APIs within different software tools.
- *Circular buildings design aspects are not fully covered:* design strategies are beneficial for CE implementation within the AEC industry. However, for the purpose of this study DFD was chosen as the most appropriate design strategy for circularity assessment purposes.
- *Lack of legislation to implement DFD in the design:* The scope of this research does not cover the constraints that hinder the endorsement and legislation of DFD by different authorities.
- *No common definition or structure for material passports:* The scope of this research does not cover the proposition of a definition or common structure for material passports.

The rest of the gaps identified in chapter "4.4 Identifying the gaps" and indicated in green in Table 17 will be addressed further in this study.

5.3. User stories

As systems engineering is an iterative and user centered process, it is important to analyze how the system should work from user's perspective. The previous sub-chapter *"5.2 Desk research and interviews comparative analysis"* provided primary inputs for the system by identifying the gaps to be addressed I this chapter. Moving forward with the system development it is necessary to derive the requirements based on information gathered previously. To make the requirements more precise, user stories can help to imagine how the system should work in practice. Subsequently, the steps identified from user's perspective aids to derive more specific requirements for the system. Therefore, below three user stories are presented. To simplify the process and avoid repetitive parts, stories are narrowed down in scope.

User story 1:

Architect builds an early design of a room (4 walls, floor, and ceiling) in BIM software and want to get suggestions for precise type of elements to use according to given constrains from the client, project manager or existing legislations, etc. related to project circularity. When all the elements are chosen, they want to see the scores for MCI, PCI, SCI and BCI.

Steps*:

**The steps in italic font represents intermediate steps performed by application automatically.*

1. Export the model in IFC format.
2. Access the web application.
3. Import the model in IFC format.
4. *Application converts the IFC to LBD.*
5. *Application shows model elements grouped according to type (wall, column, deck, etc.).*
6. Architect defines the desired manufacturer company, location, component entry date in displayed drop-down menus.
7. *Different drop-down menus are displayed to refine the search for each group of elements related to circularity indicators. For example, element type, mass of virgin material, life span, DFD factors, building layer, etc.*
8. Architect can choose from drop-down menu to check the available walls in the database based on information provided by manufacturer or other entities.
9. The architect can filter the available walls. For example, from the first drop-down menu "element" select wall, from the "mass of virgin material" drop-down menu he selects 10%, from the "life span" select between 10-50 years, from "DfD" select the category for example type of connection and factor 0.9 and from "building layer" dropdown menu selects structural.
10. Architect gets from the database all the walls that fulfils the filter criteria from different manufacturer and can choose the exact one for the project.
11. Architect can repeat the process for ceiling and floor
12. Architect can perform MCI for each element and get the score for all material used.
13. Architect can perform product circularity assessment for each element and as a whole.
14. Architect can perform system assessment based on combination of all elements and building layers.
15. Architect can perform building circularity assessment based on the building layer under study

Outcome: architects can perform assessment for their design even in the earliest stages.

Benefits: user saves time and can order the exact combination of material from manufacturer if the required material composition, in cast it is not available in the database.

Limitations: takes time for big projects.

User story 2:

Architect already has a design where the elements are specifically defined and wants to assess it for circularity (retrieve MCI, PCI, SCI and BCI scores).

Steps*:

**The steps in italic font represents intermediate steps performed by application automatically.*

1. Export the model in IFC format.
2. Access the web application.
3. Import the model in IFC format.
4. *Application converts the IFC to LBD.*
5. *Application finds the projects' matching elements in the database based on ID and retrieves assessment necessary data.*
6. Architects choose a building layer he wants to assess from a drop-down menu.
7. Architect can retrieve MCI, PCI, SCI and BCI scores for selected layer by a click of a button.
8. If the user is not satisfied with the score, they can check which elements gave the worst score by expanding the assessment results.
9. If the architect wants to get suggestions for not satisfactory elements, they can perform the steps 5-15 from *User story 1*.
10. Architect edits the model according to suggestions.
11. Architect performs steps above until all the scores are satisfactory.

Benefits: Better for big projects as the project elements are matched with the database elements automatically.

Limitations: To match the project elements with database elements a standard should be provided defining specific elements and giving them unique IDs.

User story 3:

A manufacturer has produced new elements and wants to enter their data into the shared RDF database.

Steps*:

**The steps in italic font represents intermediate steps performed by application automatically.*

1. Manufacturer access the Manufacturer application.
2. Manufacturer open the tab to enter manufacturer data.
3. *Application displays dropdown menus to choose the type of element/material to be entered.*
4. Manufacturer defines the type of element/material data which wants to enter to the database.

5. *Application displays a form to enter manufacturer data for selected element/material type.*
6. Manufacturer enters the data.
7. *Application parse the defined data to RDF format.*
8. *Parsed triples are stored in RDF database and are ready to be used.*

Benefits: Manufacturer data is entered in a same structure and can be easily retrieved on request.

Limitations: Current cloud storage capabilities would not be able to store such amounts of data in one storage. Therefore, the data should be divided so for example one manufacturer would have own data storage. This would raise a question of data accessibility through various APIs as well as privacy concerns and maintenance questions.

5.4. System requirements

The gaps selected to address in this thesis during the desk research and interviews analysis as well as presented user stories are translated into system requirements. Lightsey (2001, p. 35) argues that "requirements are the primary focus in the systems engineering process", therefore they should be derived with precision and based on user needs. According to *Systems Engineering Fundamentals* (Lightsey, 2001) there are six types of requirements: customer, functional, performance, design, derived and allocated. Regarding the scope of this thesis only the main functional requirements are addressed and complimented by non-functional requirements regarding the key needs for UI. Functional requirements are further divided into various groups according to Koelsch (2016). In Table 18 four types of functional requirements are indicated namely business rules, searching and reporting, algorithms, and database. However, many others i.e., authorization, authentication, audit tracking, certification, compliance, legal, regulatory, historical data, archiving, power, network, infrastructure, backup, and recovery requirements are not considered. Regarding the non-functional requirements only the core user interface requirements are addressed, in order to demonstrate main functionalities of the application.

Table 18: System requirements

Type of Functional requirements	Requirement
Business Rules	-Application shall be able to group model elements according to type.
	-Application shall provide the information about the elements/materials affecting circularity indicators negatively and give suggestions.
Searching and reporting	-Application shall be able to retrieve the data from database;
	-Application should be able to match model element ID with element ID provided in the database.
	-Application shall be able to generate a circularity Material Passport for the building.
	-The application shall be able to make use of IFC to LBD converter internally.
Algorithms	-Application shall calculate circularity indicators according to provided formulas.
Database	-Database shall be openly available to read for various stakeholders.
	-Data in the database shall be structured according ontologies.
	-Database shall integrate data from various manufactures or other relevant entities from any geographical location.
Type of non-functional requirements	**Requirement**
UI	-Application shall have model upload interface.
	-Application shall have model elements representation grouped by type interface.
	-Application shall display drop-down menus for selecting element manufacturer and location.
	-Application shall allow to define the range of time when the data about element was entered.
	-Application shall display drop-down menus for selecting circularity assessment related information about the group of elements.
	-Application shall provide buttons for circularity indicators calculations.
	-Application shall display subsequent windows for circularity indicators calculations providing more detailed information and selectable suggestions.
	-Application shall visualize the circularity calculations results.

5.5. Circularity assessment models analysis

In this section the previous reviewed assessment models will be further scrutinized with the purpose to identify the relevant requirements pertaining to the proposition of a structure in relation to material passport and database which in return facilitates the assessment process. As stated in section (4.2.1), this research focuses on the early design phase more specific conceptual and preliminary design phases. Therefore, the targeted stakeholders are (Architects, designers, suppliers, and contractors) in which they will benefit from such assessment to evaluate their designs in terms of circularity at early project stage. In addition, following (Cambier et al., 2020) assessment models classification, the assessment models which provide a score for the assessment at early design phase were chosen for the comparative review. The comparison will be based on different parameters such as: (1) Data required for the assessment; (2) Data acquired from the assessment; (3) End-of-Life consideration; (3) Circular design strategies consideration; (4) implementation benefits; and (5) Limitations. Furthermore, a description for five assessment models along with their calculation method will be conducted, similarly a comparison based on the five mentioned parameters will be provided.

5.5.1. Material Circularity Indicator (MCI)

The assessment model was developed by Ellen MacArthur Foundation and Granta Design. The developed MCI model for a product aims to measure *"the extent to which linear flow has been minimized and restorative flow maximized for its component materials"* (EMF & Granta, 2015,P.19). The model takes in consideration the technical cycle and is based on three characteristics (1) Mass of virgin material used; (2) Mass of unrecoverable waste; and (3) Utility factor measuring life span and intensity of product use. Furthermore, the MCI distinguished between linear and circular product based on scoring system of "0" and "1". "0" describes a fully linear product made only from virgin raw material with no regard for EOL scenarios and "1" describes a fully circular product made of recycled or reused components paying attention for EOL scenarios. In addition, EMF and Granta design described the actual situation for a product to have a score between "0" and "1".

The Calculation of MCI for a product depends on providing the required product data based on the three characteristics mentioned earlier. MCI relies on the bill of material (BoM) as a source for information. The calculation starts with determining the mass of virgin material used in a product (V). Data input related to the mass of finished product (M), fraction of feedstock from reused (F_U) and recycled (F_R) should be available. Moreover, to determine the second MCI characteristic related to the mass of unrecoverable waste (W) which is the waste that either can be used for energy recovery or sent for landfill. Data input related to the mass of finished product (M), fraction of mass of the product that can be reused (C_U) at its EOL, and fraction of mass of the product that can be recycled (C_R) at its EOL should be provided. In addition, the recycling efficiency has been taken into consideration to account for waste generated during the recycling process. For the third characteristic related to utility factor (X). Data input related to the life span of product (L) and use intensity (U) should be available. Aggregating the required data input the linear flow index (LFI) can be calculated based on the determination of the first two characteristics. LFI represents the linear flow extent of the material. Thus, the MCI can be computed as per Equation 1.

$$MCI = \max\,(0,(1 - LFI \cdot F(X))$$

Where:

$$\text{LFI} = \frac{V+W}{2M}$$

$$\text{X} = (\frac{L}{Lavg}).\left(\frac{U}{Uavg}\right)$$

$$\text{F(X)} = \frac{a}{X} = \frac{0.9}{X}\text{, to ensure MCI will have a value of 0.1, if LFI=1}$$

Equation 1 The calculation of material circularity indicator, (EMF & Granta, 2015,p.25)

5.5.2. Building Circularity Indicator (BCI)

The assessment model was developed by Verberne (2016) based on the material circularity indicator developed by EMF & Granta Design (2015). The aim of this assessment model is to measure the building level of circularity, providing an indication of the building performance towards the transition from linear to circular model. Different key performance indicators (KPI's) related to circularity were identified by Verberne based on interviews and expert panel Table 19. The KPI's were classified into three categories (1) Technical requirements; (2) Preconditions; and (3) Drivers.

Table 19: Classification of KPI's for building circularity. Adapted from (Verberne, 2016)

Technical requirements	Preconditions	Drivers
Type of input & type of output (6R-model)	Material Health / toxicity	Material scarcity
Technical lifetime	CO2-footprint / emissions	Potential financial value
Disassembly possibilities (6S-model)	Renewable energy usage	Future reuse possibilities (second-hand market)
Cycles (technological & biological)	Environmental impact	-

The assessment model focuses on materials and products in addition to their interconnection. The model is based on the technical requirements identified and the assessment is based on a score system between "0" being fully linear and "1" being fully circular (Verberne, 2016). In addition, the assessment is based on four steps calculations. First, the calculation of material circularity indicator (MCI). Second, the calculation of the product circularity indicator (PCI) utilizing (Durmisevic Elma, 2006) design for disassembly factors (DFD). Third, the calculation of system circularity indicator (SCI). Fourth the building circularity indicator (BCI), the four steps and the three KPI's can be seen in Figure 21.

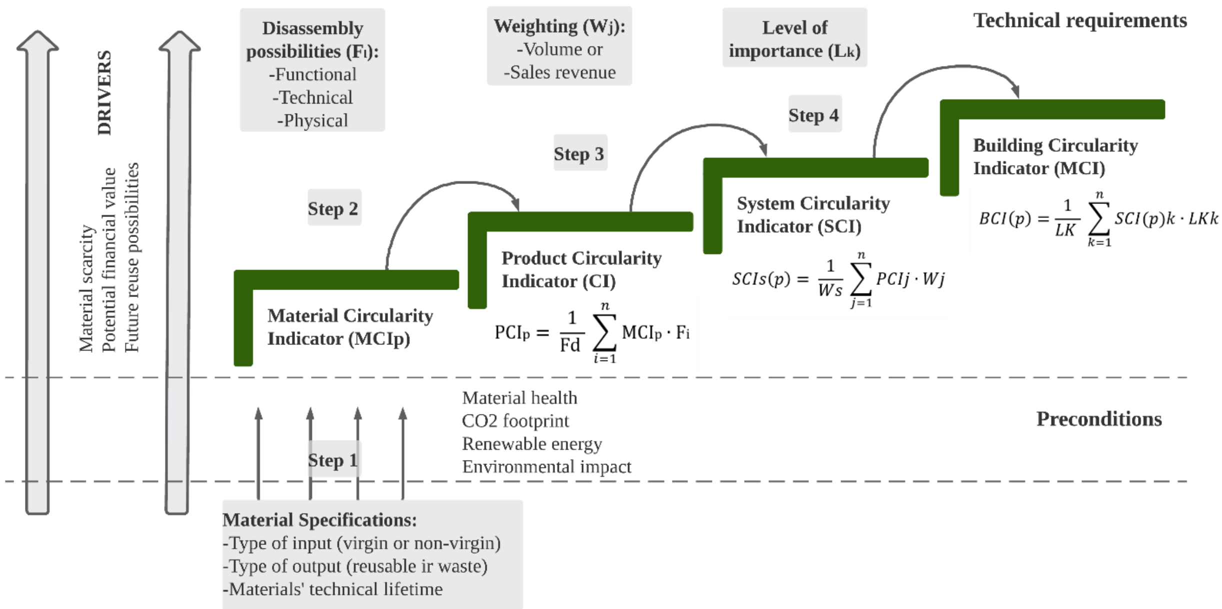


Figure 21: Conceptual structure for the building circularity assessment model adopted from (Verberne, 2016)

Moreover, each step encompasses different building information requirements to perform the calculation. Verberne utilized the BoM for this purpose as a source of the building information. Moreover, aggregating the needed information the four steps calculation can take place.

Starting with the first step, MCI calculation is similar to that from Ellen MacArthur Foundation & Granta Design (2015). Data input related to the mass of non-virgin material (V), mass of unrecoverable waste (W) in terms of future reuse, remanufacture, refurbish, and recycle. Utility factor (X) considering the technical life (L) and excluding the intensity of use (U). Furthermore, based on the available data, the linear flow index (LFI) can be calculated, and material circularity indicator can be determined as per Equation 2.

$$MCI_p = \max(0, (1 - LFI_p \cdot F(X_p))$$

Equation 2 The calculation of material circularity indicator, (Verberne, 2016, p.64)

The second step is to calculate the PCI, in this step the interfaces and connections between the products are being considered. According to Verberne, the MCI is considered as the "theoretical" value and PCI as the "practical" value for product circularity. PCI is calculated based on MCI determined in the first step and DFD factors. According on (Durmisevic Elma, 2006) study the DFD factors are divided into functional, technical and physical decomposition, assigning weight for each DFD factor (F_i), from "0" having worst impact on disassembly and "1" having the best impact. Verberne endorsed seven DFD factors for the purpose of the assessment. PCI is calculated by multiplying each MCI with DFD weighted factor and divide the sum by the number of DFD considered (F_d), as per Equation 3.

$$PCI_p = \frac{1}{Fd} \sum_{i=1}^{n} MCI_p \cdot F_i$$

Equation 3 The calculation of product circularity indicator, (Verberne, 2016, p.68)

The third step is to calculate the SCI, the calculation is based on MCI theoretical and PCI practical calculated in previous two steps. Product mass is used as a normalizing factor. The SCI is calculated for each building layer as specified by (Brand, 1995). In addition, both theoretical and practical values are being determined by multiplying each MCI with W_j and divide the sum by total product mass as per Equation 4 and Equation 5.

$$SCIs(t) = \frac{1}{\mathrm{Ws}} \sum_{j=1}^{n} \mathrm{MCI_j} \cdot \mathrm{W_j}$$

Equation 4 The calculation of theoretical system circularity indicator, (Verberne, 2016, p.68)

$$SCIs(p) = \frac{1}{Ws} \sum_{j=1}^{n} PCIj \cdot Wj$$

Equation 5 The calculation of practical system circularity indicator, (Verberne, 2016, p.68)

The last step is to calculate the BCI, based on the previous SCI calculated for each building layer. Verberne claimed based on his study that products with shorter life span are more relevant in terms of circularity. Therefore, each building layers was assigned a level of importance based on its life span as shown it Table 20.

Table 20: Building layers with respective level of importance. Adapted from (Verberne, 2016)

Building layer	Level of importance
stuff	1
space plan	0.9
services	0.8
skin	0.7
structure	0.2
site	0.1

Based on that BCI is determined by multiplying SCI theoretical and SCI practical by the level of importance of each building layer (LK) as per Equation 6 and Equation 7.

$$BCI(t) = \frac{1}{LK} \sum_{k=1}^{n} SCI(t)k \cdot LKk$$

Equation 6 The calculation of theoretical building circularity indicator, (Verberne, 2016, p.70)

$$BCI(p) = \frac{1}{LK} \sum_{k=1}^{n} SCI(p)k \cdot LKk$$

Equation 7 The calculation of practical building circularity indicator, (Verberne, 2016, p.70)

5.5.3. Madaster Platform Circularity Indicator (CI)

Madaster circularity indicator was developed with the aim to enhance building's circularity design and value. It is based on MCI developed by (EMF & Granta Design, 2015). CI is based on three principles (1) The use of secondary materials; (2) Extending the useful life of products; (3) Material recovery (reuse or recycle) at products EOL. Moreover, Madaster online platform functions as a repository for storing building materials and products related information registered in what so called material passports. In addition, it functions as a "marketplace" promoting the utilization of used building materials and products (Madaster, 2018). The calculation of CI is covering the building through three different phases namely (1) Construction phase; (2) Use phase; (3) End-of-Life phase. For the data input, Madaster platform relies on IFC open standard and excel spread sheets as the source for the relevant building data. Different requirements are needed for the calculation of CI at the three phases of building life.

Starting with the construction phase, which the objective is to use 100% non-virgin materials. Data input as a percentage of the product mass (M), related to the fraction of recycled feedstock (F_R)taking into consideration the efficiency of the recycling process and the waste generated during the process, fraction of reused feedstock (F_U), and fraction of rapidly renewable feedstock (F_{RR}) used in the manufacturing process should be provided. Further, CI for construction phase can be calculated as per Equation 8.

$$CI\ Construction = F_R + F_{RR} + F_U$$

Equation 8 The calculation for circularity indicator at construction phase, (Madaster, 2018)

For the second phase, the use phase, which the objective is to utilize the product and extend its average life span. Data input related to the potential useful life of the product and the building layers average life span based on (Brand, 1995) should be available. Further, CI for the use phase can be calculated as per Equation 9.

$$CI_{\ Use} = \frac{L}{Lav}$$

Equation 9 The calculation for circularity indicator at use phase, (Madaster, 2018)

For the third phase, the End-of-Life phase, which the objective is to optimize the reuse of materials and products. Data input as a percentage of product mass (M) related to the fraction of materials that can be reused (C_U) at its EOL, fraction of materials that can be potentially recycled (C_R) at its EOL taking into consideration the efficiency of the recycled process (E_C). At this phase DFD is considered as well, investigating the possibility to extract building component for future reuse. Three DFD factors are being investigated (1) Accessibility to the joints and ease of dismantling without damaging other building parts; (2) Dismantling is possible using standard tools without damaging other parts; (3) Product assembly is based on prefabricated mounting points. Further, CI for the End-of-Life phase can be calculated as per Equation 10.

$$CI_{\ End\text{-}of\text{-}Life} = C_R . E_C + C_U$$

Equation 10 The calculation of circularity indicator at End-of-Life phase, (Madaster, 2018)

Moreover, following (EMF & Granta Design, 2015) MCI calculation method, the building CI can be determined. Data input provided to calculate the CI for the three different phases can be used to calculate the linear flow index and utility factor. Further, building CI can be as per Equation 11.

$$CI = 1- LFI \cdot FX$$

Equation 11 The calculation of circularity indicator for building, (Madaster, 2018)

The CI score is based on a scoring system demonstrating the degree of building circularity between "0%" and "100%". "0%" represents a building constructed from virgin material and products only with consideration to EOL scenarios. On the other hand, "100%" represents a building constructed from secondary materials and products with consideration of EOL scenarios and high level of reuse (Madaster, 2018).

5.5.4. Platform CB'23

The aim of this model is to highlight the important features for circular construction. Therefore, core indicators were introduced for measuring circularity in the construction industry (Platform CB'23, 2019). Despite the fact that this assessment model is still in its development phase and is not considered as a tool that provides a final result related to building circularity it was decided to include it in the review because of its core indicators identified that can be integrated with other circularity assessment models. For example, the core indicators can be utilized for MCI calculation developed by (Ellen MacArthur Foundation & Granta Design, 2015). The core method is based on three objectives for circular construction such as: (1) protect against depletion of material stock; (2) protect the quality of the environment; (3) protect existing value. Furthermore, Platform CB'23 distinguished between two sets of indicators "Process indicators", measuring the performance towards utilizing circularity and "impact indicators" measuring the effect of such utilization. This measurement method focuses on the impact indicators to measure the extent of which the construction activities adhere to the three main objectives identified by platform CB'23. The core indicators are divided into three categories matching the three objectives. The first category is related to quantity of material used from primary, secondary, renewable, non-renewable, and scarce material. Quantity of material available for reuse and recycle, the adaptive principles are considered mainly spatial, functional, and technical adaptability. The second category is related to the influence on the environment. The third category which is at the time of writing this report is under development related to quantity of existing value. Moreover, the end result of the measurement method should provide minimum two outcomes out of three possibilities specified by platform CB'23 such as (1) list of what is expected from each indicator; (2) report for adaptive capacity.

5.5.5. Predictive Building Circularity Indicator

Cottafava & Ritzen (2020) adopted both MCI and BCI developed by EEMF & Granta Design (2015) and Verberne (2016) with the aim to elaborate the embodied energy (EE), Embodied Carbon (EC) and design for deconstruction (DFD) aspects into the circularity assessment. On a Macro level considering the impact of EE, EC, and the mass of used materials. On the Micro level as the association between the environmental impact and DFD. On the Meso level as the assessment criteria for determining the potential reuse of materials. Regarding the data input this assessment model relies on both BoM as a source for building data and environmental data from the Inventory of Carbon and Energy, v2.0 (ICE) database as a source for EE and EC data. Two indicators were introduced the BCI and predictive BCI with both full and simplified versions. What differentiate between both indicators is the incorporation of DFD in the MCI calculation and the use of simplified version of Durmisevic Elma (2006) DFD factors (f_i). Further, PBCI can be calculated as per BCI method except the introduction of DFD factors in the MCI calculation. The assessment result revealed that circularity analysis should not focus only on mass but instead include EE and EC in the assessment. The incorporation of DFD with MCI aid in better decision making regarding the recovering potential of building components. Thus, this model provides more realistic results in terms of material impact on the environment and the better prediction for material recovery.

5.5.6. Comparative analysis

Following the description of the five assessment models, comes the need to consider the points of similarities and differences between them. The five assessment models will be compared on the basis of the five parameters previously mentioned, namely (1) Data required for the assessment; (2) Data acquired from the assessment; (3) Circular design strategies consideration; (4) End-of-Life consideration; (5) implementation benefits; and (5) Limitations.

Based on the above description of the five assessment models, it can be inferred that most of the assessment models are based on the MCI developed by (EMF & Granta Design, 2015). The MCI assessment model mainly focuses on material, product, and company level. On the other hand, assessment models such as Verberne covers the assessment of building circularity assessment from different levels. For instance, MCI, PCI, SCI and BCI. Madaster platform covers circularity at different life phases of a project (Construction, use and EOL phases). Platform CB'23 documents important circularity data that can be used as an input with other assessment models. Additionally, Cottafava & Ritzen covers the environmental impact is not limited to the mass of used material but also from EE and EC perspectives. Furthermore, the input method related to building information is quite the same. Four out of the five models rely on BoM Excel formats as a source for data. In addition, Master platform utilizes IFC open standard along with BoM as well. Moreover, as MCI is the assessment model with the most contribution to the development of other models there are similarities with the assessment output for most models. For example, amount of virgin material used, amount of recovered material (reused or recycled) used, amount of unrecoverable waste, amount of potential material recovery (potential reuse or potential recycle). In addition, most of the models provide a circularity assessment core, indicating the degree of building circularity.

In relation with circular design strategies. Verberne, Madaster implemented DFD criteria in their estimates, and Platform CB’23 considered adaptive capacity (DFD and DFA) as well. In addition, the assessment models paid careful attention to the EOL scenarios mainly (reuse and recycle), considering the potential recovering output. With respect to the implementation benefits, the assessment models contribute to evaluate the performance towards the transition from linear to circular in terms of measuring circularity of material, products, and buildings. Furthermore, designers will benefit from such models in order to determine early the circularity of their design, which in turn contributes positively to the environment. Moreover, the utilization of platform such as Madaster will lead to raise the awareness regarding the use of non-virgin materials and products as it serves as a “marketplace” where information related to different materials and products can be found. There are, however, some limitations accompanying such models. For instance, models still rely on Excel format and few on IFC open standard as a source of their information. Most of the building circularity indicators are not widely tested, still in their development phase or are intended for commercial use. Table 21 offers a summary for the five assessment models based on the five parameters.

Table 21: Comparative analysis for five assessment models based on five parameters

Parameters	**Assessment models**				
	BCI	**MCI**	**CI**	**Platform CB’23**	**PBCI**
Developed by	- Verberne (2016)	- EMF & Granta (2015)	- Madaster (2018)	Platform CB’23 (2019)	Cottafava & Ritzen (2020)
Data required for the assessment	- Relies on BoM as a source of building information --------------------------- - Amount of non-virgin feedstock --------------------------- - DFD factors --------------------------- - Life span of material or product --------------------------- - Mass of material or product --------------------------- - fraction of material or product for future reuse, remanufacture, refurbish, and recycle	- Relies on BoM as a source of material and product information --------------------- - Amount of non-virgin feedstock --------------------- - Life span and use intensity of material or product --------------------- - Mass of material or product	- Relies on BoM and IFC as a source of building information --------------------- - Fraction of recycled, renewable, and reused feedstock --------------------- - Life span of material or product --------------------- - Product mass --------------------- - fraction of material or product for future reuse, and recycle --------------------- - Efficiency of the recycled process --------------------- - DFD evaluation --------------------- - Amount of non-virgin feedstock	- Relies on BoM as a source of material information ------------------- - Amount of virgin material ------------------- -Amount of secondary material (reused recycled) Amount of scarce and non-renewable material	- Relies on BoM and expert audits as a source of building information ----------------------- -relies on ICE database as source for EE and EC information ----------------------- - Amount of non-virgin feedstock ----------------------- - DFD factors ----------------------- - Life span of material or product ----------------------- - Mass of material or product ----------------------- - fraction of material or product for future reuse, remanufacture, refurbish, and recycle

Data acquired from the assessment	- Amount of virgin feedstock ---------------------------- - Amount of unrecoverable waste ---------------------------- - MCI, PCI, SCI and BCI assessment score system between "0" and "1"	- Amount of virgin feedstock --------------------- - Amount of unrecoverable waste --------------------- - Score system between "0" and "1"	- Amount of virgin feedstock and unrecoverable waste ---------------------- - CI for (construction, use and End-of-life) phases assessment score system between "0%" and "100%"	-Amount of material for reuse and recycle -------------------- -Amount of unrecoverable waste	-Amount of virgin feedstock ------------------------ - Amount of unrecoverable waste ------------------------ - MCI, PCI, SCI and BCI assessment score system between "0" and "1"
End-of life considerations	- Considers future reuse, remanufacture, refurbish, and recycle	- Considers future reuse, remanufacture, refurbish, and recycle	- Considers reuse and recycle	- Considers reuse and recycle	- Considers reuse, recycle, remanufacture, reuse, and repair
Circular design strategies	- Considers DFD factors	- Covers disassembly as part of recycling efficiency	- Considers DFD evaluation	- Considers building adaptive capacity and DFD concepts	- Considers DFD factors
Implementation Benefits	- Covers the building circularity assessment from different levels MCI, PCI, SCI and BCI ---------------------------- - can be utilized in early design stage to evaluate design circularity ---------------------------- - Provides an indication of the performance towards the transition from linear to circular model ---------------------------- - Developed based on an existing (MCI) assessment model	- Widely accepted and measure how well a product or company performs in the context of a circular economy --------------------- - Provides an indication of the performance towards the transition from linear to circular model --------------------- -Used as base for development of different circularity assessment models	- Covers circularity at different life phases of a project (Construction, use and EOL phases) ---------------------- - enhance building's circularity design and value ---------------------- - Promotes the use of material passports ---------------------- - functions as a "marketplace" promoting the utilization of used building materials and products	- Documents important circularity data that can be used with other assessment models -------------------- - Covers wide range of indicators related to (material, environment, and value)	- Covers the building circularity assessment from different levels -Considers EE, EC and mass of used material investigating the environmental impact ------------------------ - Improve the assessment process for identifying material recovery output
Limitations	- Not widely tested ---------------------------- - Does not consider the use intensity for material and product ---------------------------- - Relies on excel spreadsheets as BoM format	- Measures material and product circularity with no specific consideration for building --------------------- - Does not consider circular design strategies within the calculations --------------------- - Considers waste generated from reuse and recycle only	- Subjective consideration for DFD factors --------------------- - Relies on excel spreadsheets as BoM format ---------------------- - Relies on IFC to capture material circularity information ---------------------- - Commercial platform ---------------------- - Closed source database	- Only focus on calculation for material related indicators -------------------- -Does not provide a circularity assessment result	- Difficulty to calculate EE and EC ------------------------ -Relies on single source for environmental data to retrieve EE and EC

5.5.7. Selected models and indicators

Most important input points required to perform a circularity assessment for a building were identified from the different assessment models reviewed. The assessment models have similar objectives for promoting the assessment of circularity. However, for the purpose of this research, the approach, and requirements from two assessment models will be aggregated with the aim to suggesting a structure in relation to material passport and database as stated earlier.

It is obvious now that MCI developed by EMF and Granta design is the most commonly used assessment model for materials and products. It refers to the technical cycles for materials and products. Therefore, it was decided to implement the following points from MCI assessment model:

- Mass of finished product (M)
- Mass of virgin material (V)
- Fraction of the mass of reused sources (F_U)
- Fraction of the mass of recycled sources (F_R)
- Fraction of the mass of the product being collected for recycling at the end of its use phase (C_R)
- Fraction of the mass of the product being collected for reuse at the end of its use phase (C_U)
- Efficiency of the recycling process (E_C)
- Product's lifetime (L)
- Industry's average lifetime (L_{avg})

Moreover, Verberne assessment model considered the building levels in consideration. In addition, the DFD factors introduced by (Durmisevic Elma, 2006) were utilized to calculate practical PCI and considered (Brand, 1995) building layers for the calculation of SCI and BCI. It was therefore, decided to adopt the following points from Verberne assessment model:

- The approach to include different building layers to calculate PCI, SCI and BCI
- Include DFD factors in the calculation of PCI
- The approach of aggregating all the calculated PCI for each building layer to calculate SCI
- The approach of utilizing the system dependency (L_K) to calculate BCI

Moreover, after analyzing the DFD factors adopted by Verberne, it was determined to incorporate some factors based on three criteria. First, design phase, as mentioned earlier this research focuses on early design phase. According to Durmisevic Elma (2006) *"functional decomposition cannot be made during the conceptual design phase, which deals predominantly with the functionality of the assembly, because additional analysis is needed"* (p.170). Therefore, factors that can be decided at early design phase were included. Second, the source of information that is the person responsible for the information. Third, the possibility to store the related factors. Some factors are based on subjective judgment. For instance, the decision on the sequence of assembly, clustering different building components to create a function. Table 22 defines the DFD aspects, sub-aspects and the included DFD factors highlighted in green, based on the three criteria.

Table 22: DFD aspects , sub-aspects and the included DFD factors (highlighted in green)

Aspect	Sub-Aspect	Design phase	responsibilty	Subjectivity
Functional Decomposition	*Functional separation*	Detailed after configuring the differeent technical and physical configuration	Designer	Subjective
	Functional dependence			
Systematization	*Structure and material level*	Detailed after configuring the differeent technical and physical configuration	Designer	Subjective
	Clustering			
Base Element	*Base element specification*	Detailed Design	Designer	Subjective
Life Cycle Co-ordination	*Use life cycle co-ordination*	Early design phsae	Designer	Subjective
	Technical Life cycle co-ordination	Early design phsae	Designer	Subjective
	Life cycle of components	Early design phsae	Designer	Subjective
Relational pattern	*Position of relations in relational diagram*	early/detailed	Designer/Manufacturer	Subjective
Assembly	*Assembly direction based on assembly type*	early/detailed	Designer/Manufacturer	Subjective
	Assembly sequences regarding material levels	early/detailed	Designer/Manufacturer	Subjective
Geometry	**Geometry of product edge**	**early/detailed**	**Designer/Manufacturer**	**Objective**
	Standardization of product edge	**early/detailed**	**Designer/Manufacturer**	**Objective**
Connection	**Type of connection**	**early/detailed**	**Designer/Manufacturer**	**Objective**
	Accessibility to fixing and intermediary	**early/detailed**	**Designer/Manufacturer**	**Objective**
	Tolerance	early/detailed	Designer/Manufacturer	Subjective
	Morphology of joints	**early/detailed**	**Designer/Manufacturer**	**Objective**

5.6. Material Passport for circularity assessment

During the analysis of circularity assessment models and indicators, Ellen MacArthur model together with five Design for Disassembly factors most relevant for early design stage were selected for further development of system framework proposed in this thesis. As it was identified in the literature review systematic data collection and documentation holds significant value for correctly functioning system and its reusability. Therefore, the chosen model parameters should be reflected in a Material Passport which serves as a structured digital set of data and provides systematic documentation.

As this thesis project is specifically concentrated on circularity assessment based on technical indicators for early design stage, the further related factors are proposed for Material Passport to reflect this purpose. This *ad hoc* definition is necessary to proceed with database structuring while ensuring that all relevant data will be present. However, for the future research the proposed number of factors could be extended for broader perspective on Circular Economy at all stages of project design.

Literature review showed that currently there are many propositions for material passport structure both from academia and various organizations. Munaro et al. (2019) proposed a Material Passport for wood frame constructive system in Brazil. According to this thesis research this type of structure combined from several general types of information is seen in various sources like Miu et al. (2020), C2C, CIRMAR or Turntoo with slight variations. The eight information types proposed by Munaro (2019) are: (1) general data, (2) security measures, (3) sustainability, (4) use and operation, (5) disassembly guide, (6) reuse potential, (7) history and (8) other information. However, looking from the perspective of this project, the information provided by this passport is not broad enough on specific types, i.e., disassembly.

Project BAMB (Heinrich & Lang, 2019) proposed structure seems to be the most extensive so far including not only the biological, physical and chemical material properties but as well reflecting on related processes. However, further research showed that BAMB passport is missing structure for some key elements like disassembly factors, which are included to the chosen assessment model. On the other hand, Verberne (2016) introduced a structure called BOM (Bill of Materials) which can be seen as the factors to be included in Material Passport required for circularity assessment. BOM is less extensive compared to BAMB but contains all the necessary information for the assessment model chosen for this thesis.

Required data inputs form manufacturer side are represented in Figure 22. As was mentioned before this template characterizes only the data needed for early design assessment and later could be supplemented by additional factors which could also be defined by the designer himself.

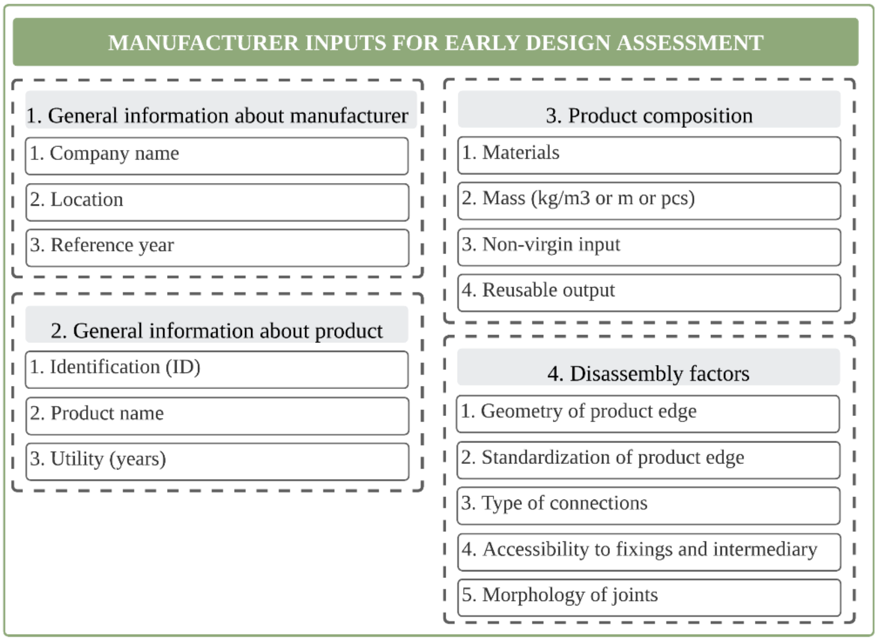


Figure 22: Manufacturer data inputs for early design

5.7. Retrieving the data

This sub-chapter deals with the system inputs and the ways how the circularity assessment related data can be retrieved. Firstly, looking from the main user side the IFC open standard is analyzed in order to find the benefits and pitfalls related to the assessment technical implementation. Subsequently, the existing data sources are analyzed. Semantic Web and Linked Open Data technologies are introduced as an alternative to overcome the data management issues and therefore, further the existing ontologies are examined with relation to the assessment model in order to structure the manufacturer provided data.

5.7.1. IFC Open Standard

Since the technical requirements and the DFD factors for conducting the circularity assessment have been indicated on the basis of the comparative analysis performed in the *"5.5 Circularity assessment models analysis"* chapter. A general overview of IFC capabilities to capture the required data related for the circularity assessment will be provided. As stated earlier the attention of this study is not to suggest a modification or an extension to the IFC schema. Yet, it is important to examine the potential of such exchange format to capture the identified requirements for the assessment.

IFC is the most widely used data model with the purpose to capture building data and enhance interoperability between different BIM software. It was developed by International Alliance for Interoperability (AIA), currently known as buildingSMART and is based on ISO-STEP, exchanged through STEP Physical File (SPF) format and the schema is modeled using EXPRESS modelling language (Borrmann et al., 2018; Sacks et al., 2018). According to Borrmann et al. (2018) IFC exchange format is able to present "Geometry" and "Semantics" of a building using object-oriented modeling. Using this approach entities, attributes and the relationships to other entities can be introduced. The conceptual organization of IFC consists of several layers, namely domain, interoperability, core, and resource layers (For a more general overview see Appendix B, demonstrating the conceptual organization for IFC4.3 RC2 layers).

Domain layer: Highest layer which contains domain specialized entity definitions related to products, processes, or resources (Borrmann et al., 2018; BSI, n.d.-b). Is based on IFC4.3 RC2 which is the latest release at the time of writing, with current status as "candidate". Defines the domain layer for structural analysis, structural element, architecture, plumbing and fire protection, building controls, ports and waterways, construction management, rail, electrical, road and HVAC (BSI, n.d.-b).

Interoperability layer: This layer contains general product entity definitions related to products, processes, or resources such as IfcWall, IfcColumn, IfcBeam, etc. (Borrmann et al., 2018; BSI, n.d.-b).

Core layer: This layer contains most general entity definitions which can be referenced by domain and interoperability layers, a globally unique identifier (GUID) is assigned for entities, additionally, incorporates the kernel comprising of three schema extensions namely, product, process, and control extensions (Borrmann et al., 2018; BSI, n.d.-b).

Resource layer: This is the lowest layer which contains resource definitions, but with no GUID specified. To name some, geometry resource, quantity resource and material resource (Borrmann et al., 2018; BSI, n.d.-b).

Moreover, with an overview of the conceptual organization of IFC layers, comes the need to comprehend how the IFC schema represents the building elements and what attributes it can hold. Figure 23 represents a general overview of how a "Wall" can be defined using IFC data model.

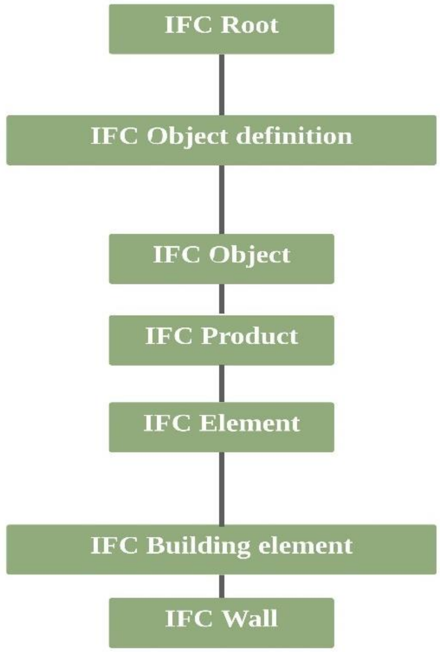


Figure 23: Example of IFC structure to define a wall. Adapted from (Sacks et al., 2018)

The following is a general description of the figure endorsed from (Borrmann et al., 2018; Sacks et al., 2018) description. It can be noticed from Figure 23 that it starts with IfcRoot in which a GUID can be assigned along with other information such as ownership and version history. In "IfcObjectDefinition" wall components are identified such as doors and windows. "IfcObject" provides a link to the wall properties. "IfcProduct" defines the wall's location and shape as it relates to "geometric" or "spatial context". "IfcElement" defines the relationships with others such as bounding relationships, similarly, defines if the wall contains any openings and its filling. "IfcBuildingElement" contains sub-entities for building elements such as "IfcWall" and "IfcColumn".

Borrmann et al. described that with the use of attributes different characteristics for objects such as wall elements can be assigned within the IFC schema. For instance, the height and width using "OverallWidth" and "OverallHeight" static attributes. However, they argued that other important characteristics are not covered with those static attributes as it creates issues to the schema. additionally, software vendors tend to provide basic entity of the properties in their applications. Moreover, it can be inferred that the technical requirements identified to conduct the assessment are not covered within the static attributes defined within the schema.

Another approach of defining properties is the use of dynamic properties also known as the "P-set" which can be assigned to an object using IfcRelDefinesByProperties (Borrmann et al., 2018). Buildingsmart through their website provides an access to different P-Sets definitions. PSetWallCommon defines for example, "AcousticRating", "Fire Rating", "LoadBearing" properties. Table 23 offers a summary of the quantity use definition and Pset Wall common definition for IfcWall.

Table 23: Quantity use definition and property set use definition for IfcWall. Adapted from (BSI, n.d.-b)

Quantity use definition	Property set Definitions:
NominalLength	Reference
NominalWidth	AcousticRating
NominalHeight	FireRating
GrossFootprintArea	Combustible
NetFootprintArea	SurfaceSpreadOfFlame
GrossSideAreaLeft	ThermalTransmittance
NetSideAreaLeft	IsExternal
GrossSideAreaRight	ExtendToStructure
NetSideAreaRight	LoadBearing
GrossVolume	Compartmentation
NetVolume	-

It can be noticed that even in the dynamic property (Pset) definitions technical requirements identified to conduct the circularity assessment are not covered. Moreover, despite the fact that IFC lack the coverage of the technical indicators required for the circularity assessment. It is considered for further development as it is considered the widely accepted standard for building information exchange.

5.7.2. Existing Data Sources Analysis

Having the assessment model chosen and requirements for material passport transferred, comes the need to find out where that information about building components can be found. Based on the literature review and interviews it was identified that unfortunately, a common practice in the industry to store material data is still relying on closed tabular data sheets and file formats like PDFs. On top of that various governmental, non-profit, and commercial databases were identified carrying relevant data for sustainability, LCA, waste management or Circular Economy.

This type of databases which were the most extensive and held the most relevant information for the topic were listed and examined in Table 3 chapter "Buildings as Material Banks". However, as further analysis showed none of the databases currently holds all the necessary information for chosen circularity assessment model. As a rule, all of the reviewed datasets were concentrated on sustainability related information like for example, Global Warming Potential (GWP) or carbon footprint which can be found in any of those databases. However, technical input and output indicators for circularity assessment were hardly found. Some of them like disassembly factors were not presented anywhere.

Another issue was identified linked to the extensiveness of the datasets. Many of the databases identified, were based on specific country, therefore held information mostly collected from that country suppliers. Furthermore, some datasets were very limited regarding to the number of products included. On the other hand, databases like Exiobase or IMPACT World+ carry internationally collected data from many countries. However, it is focused on material flows rather than specific product leading to information that is too general to use for assessment.

The database accessibility comes as a very important factor as well. Currently there are many vendor specific solutions where the data can be retrieved only provided by the vendor and of course, under a paid license. These types of databases are impossible to combine without different vendors' agreement or user devoted to purchasing all of the licenses. On the contrary, open-license databases are also presented in different structures and formats, which makes them hard to combine to one knowledge base.

European project Horizon initiated Buildings as Material Banks (BAMB) database seems to present the most information relevant to circularity assessment so far. Furthermore, it shows an initiative to connect documents like EPDs or MSDS to components providing more extensive datasets. Even So, the database is still under development and at the current state no information for disassembly factors or renewable materials used to be included was found.

In conclusion, after examining the current ways of data storage and existing databases it becomes clear that there are some significant issues for data management in AEC industry. Most of the data is still stored in closed datasets and in various formats. Furthermore, all of the datasets are scattered and do not present a common structure, which would allow to make use of the combination between them. Finally, from the perspective of chosen assessment model, some of the data necessary for assessment was nowhere to be found. These, issues lead to the need of a common data environment where all of the required data would be present in a shared structure and format as well as to be available for all users. The pros and cons for some databases, which were found to hold the most relevant information are presented in Table 24.

Table 24: Pros and Cons of some existing sustainability, LCA, waste management or CE related databases

Database	Advantages	Limitations
Oekobaudat, Ibu Data, EPD International, EPD Italy, EPD Norge Digi	-Openly available, no license required. -Available in different countries in same format, which makes it more extensive. -Holds some information relevant to circularity assessment.	-Not machine-readable. -Miss a great deal of information relevant to circularity assessment. -Some materials/components in the same database hold different amount of information. -Country based database hold information mostly from that country suppliers.
Exiobase, IMPACT World+	-Openly available, no license required. -Provides some information that is not listed in EPD based databases, like scarce materials used or toxicity. -International, include data from many countries. -Excel based datasets can be mapped to RDF datasets.	-Input-output databases concentrated on material flow rather than single element properties. -Miss a great deal of information relevant to circularity assessment. -Presented in tabular data like separate Excel files or ZOLCA files to be opened in LCA software.
SundaHus	-Holds some information needed for circularity assessment (same as EPD based + toxicity).	-Commercial, needs paid license. -Not machine-readable. -Closed to a vendor. -Miss a great deal of information relevant to circularity assessment. -Country based.
Quartz	-Openly available, no license required. -Available in Excel and JSON.	-Very limited dataset only for 102 products. -Has no information needed for selected circularity assessment model.
BAMB	-Openly available, no license required. -International, include data from many countries. -Holds the most circularity assessment relevant data compared to other databases. -Incorporates data from EPDs via linking.	-Not available yet, under development. -Not machine-readable. -Miss information about renewable materials used and disassembly factors.

5.7.3. Semantic Web and Linked Open Data

Sematic Web (SW) and *Linked Open Data (LOD)* technologies are advocated to overcome current data management issues by providing an open common data platform. *Semantic Web* includes a set of technologies which are necessary in order to bring semantic data to *World Wide Web (WWW)* (Costa Jutglar, 2017). These technologies are illustrated in *Semantic Web Stack* presented by Tim Berners-Lee (WWW past & future, 2003). *Semantic Web Stack* shown in Figure 24 or later as well referred as *Layer Cake* (Idehen, 2017) includes five categories represented by different technologies. The bottom *representation* category is combined from URIs (Uniform Resource Identifiers)/IRIs (Internationalized Resource Identifiers) which represents the concepts (terms) and RDF/XML which represents the semantic metadata (Costa Jutglar, 2017). RDF (Resource Description Framework) is named as a core of the SW which can be explained as a *"flexible and generic language that allows to represent and combine information from diverse knowledge domains"* (Pauwels et al., 2017, p. 148).

RDF graphs are also called triples and are combined from three parts: subject, predicate, and object. Each subject represents an individual which is identified by URI, while predicate represent the connection between the subject and object which is as well identified by URI. Meanwhile RDF object can be identified both by URI and a literal. RDF graph can be serialized by different syntaxes like RDF/XML (.rdf), N-Tripples (.n_t), Turtle (.ttl) or Notation-3 (.n3) (Pauwels et al., 2017). Turtle files are commonly used as they provide easily human understandable structure.

Reasoning category includes core ontologies RDFS, OWL and rules RIF. There can be other rule languages used as well like R2RML for describing how to transform relations into RDF triples or SWRL to describe "how to dynamically materialize new entity relationships based on existing data" (Idehen, 2017). Ontologies are languages providing means to describe classes, relationships, functions, formal axioms and individuals (Costa Jutglar, 2017). Classes are normally structured in taxonomies showing the hierarchy. Formal axioms helps to facilitate the automatic reasoning by enabling inference rule, which shows the real power of Semantic Web allowing *"derivation of facts that are not explicitly expressed in the ontology"* (Costa Jutglar, 2017, p. 60). Ontologies, RDF triples and rules are also represented by TBox, ABox and RBox respectively.

The *query* category includes the standard SPARQL query language. SPRAQL query language is based on SQL and is made to query information in RDF and RDFS. One of the most powerful and used SPARQL queries is SPARQL CONSTRUCT query, which allows to generate RDF graphs. "CONSTRUCT clause enables to specify the graph pattern to be generated as a result of the transformation, constructed by replacing the values of the variables, the WHERE clause enables to specify the corresponding source pattern" (Costa Jutglar, 2017, p. 83). The *reasoning* category together with *query* category builds up the *Web of Linked Data*.

The last two categories are *trust* including unifying logic, crypto, proof layers and *interaction* category which concerns about user interface and applications layer. *Crypto* layer addresses the transmission security. *Unifying logic* or first-order-logic (FOL) which *"serves as the conceptual schema around which data is modelled and understood"* (Idehen, 2017). FOL enables some powerful features of SW like Boolean operators, two quantifiers or representations expressed by English words. *Proof* with the *two-factor-authentication* provides the foundation for *trust* which is directed to data privacy. Finally, *User Interface and Applications* or later known as *Smart (Cognitive) Applications and Services* should be built declaratively and consistent with widely known MVC (model, view, controller) pattern (Idehen, 2017). Regarding this thesis, the last two categories will be not addressed due to the complex nature in relation to the scope of the project.

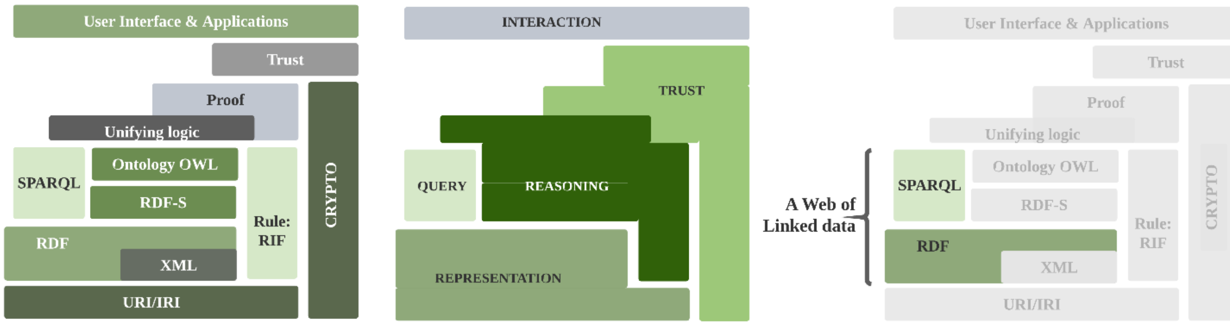


Figure 24: Semantic Web Stack and Web of Linked Data. Adopted from (Berners-Lee, 20016)

5.7.4. Ontology analysis

Ontologies are a vital part for structuring the data in the Semantic Web. Therefore, an analysis of existing ontology structures relevant for this thesis project is made. During the literature review different types of ontologies were identified which could be divided in four categories:

1. Ontologies designed to describe manufacturer product and process data.
2. Ontologies designed to describe building product data.
3. Ontologies that connect the manufacturer data with BIM data.
4. Ontologies relevant to sustainability, LCA, waste management or Circular Economy.

In the first ontology group 12 most referred ontologies describing the manufacturer data were identified dating from 2006 to 2020. These ontologies were set for a deeper analysis firstly looking if they are meant to describe the product itself, the manufacturing process or both. Secondly the suggested ontology classes, sub-classes and properties were reviewed and matched to the selected assessment model.

The manufacturer ontology analysis showed that only half of the identified ontologies describes the product itself in an expressive manner. This is an important part in regard to this thesis as for the assessment it is necessary to retrieve the data about component properties rather than its' manufacturing processes. That it is also the reason why in the ontologies which were dedicated to map the processes none or just a couple relevant classes or properties were found. In contrast, the ontologies that were focused more on describing the product showed much greater number of reusable classes. For example, DFM ontology proposed by Chang (2008) showed a nice taxonomy for describing a product including detailed descriptions for joints, spatial relationships or joining processes. MASON ontology (Lemaignan et al., 2006) provided useful classes related to product composition like raw material, semi-finished part or material resource. While ManuSquare ontology (Landolfi et al., 2018) as well introduced some sustainability measures and classes to define them.

However, none of these ontologies were found to be published online in Liked Open Vocabularies (*Linked Open Vocabularies (LOV)*, n.d.) or other Web ontology collections. Which means that the relevant classes or properties can be reused only on conceptual level and needs to be published on the Web to make real use of them. The overview of manufacturer data ontologies can be seen in Table 25.

Table 25: Overview of manufacturer data representing ontologies

Manufacturer data describing ontologies	Describe the product	Describe the processes	Includes relevant classes, subclasses, and properties for selected assessment model
DFM	+	Production process	Product; Assemblability; Fixturability; Surface Finish, Joint Feature; Joint Constrain; Joint Tolerance; Joint Shape; Contact Shape; Spatial Relationship; Joining Process;
FGMO	+	Production process	Portion of material; Pure material; Portion of chemical compound; Mixed material;
MSDL		+	
FLEXINET		+	
MCCO		+	
MASON	As a resource, no more than 1 subclass	+	Raw material; Resource; Semi-finished part; Is made of; Assembly entity; Finished part; Material resource;
ManuSquare	+	+	Assembly; Material; Indicator Coefficient; Material Coefficient; Coefficient; Supplier; Component; Item;
P-PSO	As a component, no more than 1 subclass	+	Component; Fixture; Part;
FIF		+	
MatOnto	+	New material discovery	Material; Property; Data Type;
PMPO	+	+	Portion of Raw Material, Part; Has Specified Input; Composition of Material, Surface Finish; Material; Type of Manufacturer; Postal Address; Web Address; Phone Number;
ONTO-PDM	+		Product; Related Product; Product category; Assembly Component Relationship; Next Assembly Usage;

The second ontology group is dedicated to find ontologies describing building product data. As it was identified in the literature review, recently there was a new ontology released by Wagner & Ruppel (2019) named BPO (building product ontology) in order to overcome the shortcomings of the previously used PROPS and PRODUCT ontologies. BPO makes use of ten other ontologies like BOT (Building Topology Ontology), OPM (Ontology for Property Management) or LUPO (Lightweight Upper Ontology) and is built upon SolConPro ontology. It is combined from 14 classes with related object and data properties. The main advantage of this ontology related to this research is the use of *Building Smart Data Dictionary* and the focus on representing building products, which is useful in order to find relation between BIM components and manufacturer provided data. However, the ontology itself do not give to any further extent detail necessary for circularity assessment other than general product properties.

A recent contribution describing building materials is presented by Valluru et al. (2020). Ontology named *Digital Construction Building Materials* (DICBM) is dedicated *to "represent construction and material models of building elements and to improve interoperability"* (Karlapudi & Valluru, 2019). DICBM could be combined with BPO ontology for more detailed building product representation as BPO defines the element itself, while DICBM provide vocabulary do define the materials contained by the product.

The third group of investigated ontologies was to explore proposed ontologies in order to connect BIM data with manufacturer data. These types of ontologies are important because during the assessment the user will have to import his model into the web-application to retrieve model components. These components will have to be matched with available products in the database to retrieve the circularity score. Ontologies like BAUKOM, BIMMO, ManuService or E-Commerce were created to achieve this goal for different purposes. However, the reusability of ontologies that are created to map connections between different datasets are very limited as they were created for specific use.

Finally, the last group of ontologies were researched in order to find relevant classes and properties for the circularity assessment itself. As Circular Economy is just paving its' way to the industry there were not so many works found related to it in connection with Semantic Web. Therefore, also ontologies providing relevant structure for sustainability, LCA or waste management were reviewed. However, the deeper analysis showed that ontologies designed for eco-efficient building design like SMERGY (Shayeganfar et al., 2013) or sustainable design like IASDOP (Eddy, 2013) don't have any relevant structure for this project. LCA/LCI ontology by Janowicz et al. (2015) revealed to have a few classes that could be potentially reused.

The research uncovered four ontologies having the most classes and properties necessary to assess the project for circularity. An ontology for IoT enabled decision support system by Mboli et al. (2020) proposed classes to map product's destiny, i.e. repair, remanufacture, reuse, etc. Meanwhile BONSAI ontology (Ghose et al., 2019) is focused on material flows, which can also be employed to map the material inputs and outputs for a single component. CEO and CAMO ontologies (E. Sauter et al., 2018) by default has the most relevant structures to this thesis case as they are purposely created for Circular Economy. However, some more detail structure is still missing. For example, the class of *Disassembly* is a sub class of *Technological Activities* which means that this class is just identifying the future destiny of the element but not how it will be disassembled or how easy would be the procedure, etc. Therefore, it shows a gap in ontological descriptions related to the detailed factors needed for assessment. The overview of CE related ontologies can be seen in Table 26.

Table 26: Overview of CE related ontologies

Ontology	Maps product	Maps flow	Reusable classes and properties
LCA/LCI		+	Property; Location; Has Location;
CEO		+	Product; Resource; Waste; has Input Type; Input; Input of; Output; Output of; waste of;
CAMO	+		Building Products; Chemical Recycling; Company; Disassembly; Material; Mechanical Recycling; Product; Recycling; Refurbishing; Remanufacturing; Repairing; Resources; Reusing; Upcycling; Whole Parts; Composed of; Has Condition; Has Durability;
BONSAI		+	Flow; Input Of; Output Of; Flow Object; Has Temporal Extent; Has Location;
J. S. Mboli (2020)	+		Product; Repair; Remanufacture; Cascade; Recycle; Reuse

In conclusion, now there are various ontologies available to describe building products, manufacturer data and properties related to sustainability or Circular Economy. Looking at manufacturer data defining ontologies the main issue is seen in the lack of structure for circularity factors and reusability, as the ontologies are not published. Still, some parts of the structures and taxonomies could be used to guide the new ontology creation process. From the perspective of building material ontologies, it was found that presently there are not many vocabularies to choose from. BPO was identified as the current building product defining ontology, which of course holds only the main product properties and is not related to CE. Nevertheless, it is still seen useful in order to connect BIM data with manufacturer data during the assessment. Finally, the Circular Economy related ontologies were examined. CEO and CAMO ontologies were identified as carrying the best structure for this thesis purpose. However, this research showed that none of the ontologies currently fulfils all the needs of providing data structure for storing information about necessary factors for circularity assessment.

5.8. Ontology definition for product circularity

Existing ontology analysis have identified the need for a vocabulary defining the building circularity indicators for an early design stage assessment. Therefore, this sub-chapter is dedicated to fill this gap while following Ontology Engineering guidelines presented by Suárez-Figueroa et al. (2012) and LOT (Linked Open Terms) methodology (María Poveda Villalón et al., 2019). LOT presents four stages for Ontology Engineering namely: Ontology requirements specification, Ontology Implementation, Ontology Publication and Ontology maintenance. Regarding the scope of this thesis only the first two stages are implemented. According to LOT methodology before starting to work on the ontology requirements it is important to specify the use case and identify the data exchange documentation and examples. However, these two steps where already addressed previously in chapters *"5.3 User stories"* and *"5.7 Retrieving the data"*.

5.8.1. Ontology requirements specification

The aim of this section is to specify requirements for the ontology and at the end produce the Ontology Requirement Specification Document (ORSD). The first step towards that is to define the purpose of the developed ontology. As it was identified previously, currently there is no proposition for a vocabulary covering the structure needed to define technical product circularity indicators. Therefore, the purpose of the developed ontology is *to provide all necessary product and material data for building's circularity assessment at early design stage according to selected assessment model.*

Regarding the costs of logistics, it is common to collect building products from producers located in convenient distance from the building site, unless of course the price of the logistics could be covered by the significant difference in element prices. However, one way or another it is important that the product library would contain elements from various locations. This leads to the second step in requirement definition i.e., scope. To make the solution applicable in multiple countries the ontology should be universal for entering the data to any manufacturer at any location. Thus, at the same time is worth to mention that the scope of vocabulary definition is limited to selected assessment model technical indicators and data that could be objectively entered by manufacturers.

The third step is to specify the implementation language, which in this case was decided to use W3C recommendation and most widely used web ontology language OWL. The fourth step calls for the functional requirements definition and it is recommended to derive them by the means of competency questions. According to Grüninger & Fox (1995) competency questions could be seen as a set of problems which serve to characterize ontologies to be necessary and sufficient to represent the tasks and solutions for the various components of the system. Regarding this case as set of competency questions were derived and answered, which can be seen in Table 27. The questions were focused on the main information about the product, material, manufacturer, and technical circularity indicators for the assessment. Further similar questions could be derived in order to see a more detailed view for the requirement specification, though for the purpose of this thesis the 17 questions proposed in Table 27 covers the main functionalities.

Table 27: Competence questions for BCAO functional requirements definition

Identifier	Competency Question	Answer
CQ1	What materials is Wall (ID LB1001) is made of?	Wall is made of Concrete C40 (ID C101) and Steel S355JR (ID S101).
CQ2	What is the location of Wall (ID LB1001)?	Rørdalsvej 15, Aalborg Øst, 9220, Denmark
CQ3	What is the expected life span of the Wall (ID LB1001)?	50 years.
CQ4	What is the type of Wall (ID LB1001) edge standardization?	Pre-made.
CQ5	What is the type of Wall (ID LB1001) edge geometry?	Symmetrical overlapping.
CQ6	What is the type of Wall (ID LB1001) joint morphology?	Knot.
CQ7	What is the accessibility of Wall (ID LB1001) fixings?	Accessible with causing damage.
CQ8	What type is the Wall (ID LB1001) connection?	Direct chemical.
CQ9	Which Walls have lifespan more than 50 years?	Wall (ID LB1001), Wall (ID LB1005), Wall (ID LB1007), Wall (ID LB1008), Wall (ID LB1009).
CQ10	Which Walls reusable material output is more than 30%?	Wall (ID LB1005), Wall (ID LB1006), Wall (ID LB1009).
CQ11	Which Walls have Pre-made edge standardization?	Wall (ID LB1001), Wall (ID LB1005), Wall (ID LB1009).
CQ12	How much of non-virgin input is in product's material: Concrete C40 (ID C101)?	50%.
CQ13	How much output of material Steel S355JR (ID S101) is reusable?	35%.
CQ14	What manufacturer manufactured Wall (ID LB1001)?	Manufacturer1.
CQ15	What manufacturer produced Concrete C40 (ID C101)?	Manufacturer2.
CQ16	Where the manufacturer Manufacturer1 is located?	Rørdalsvej 15, Aalborg Øst, 9220, Denmark
CQ17	What type of manufacturer Manufacturer1 is?	Pre-cast reinforced concrete elements manufacturer.

Having the competency questions identified and answered the fifth step requires to group them into categories which will further be addressed as functional requirements categories. In this case four categories were identified:

(a) Information about the product: CQ1, CQ2, CQ3, CQ14, CQ16, CQ17 (6 questions in total).

(b) Assessment information: CQ3, CQ4, CQ5, CQ6, CQ7, CQ9, CQ10, CQ11, CQ12, CQ13 (10 questions in total).

(c) Information about the material: CQ12, CQ13, CQ15, CQ16, CQ17 (5 questions in total).

(d) Information about the manufacturer: CQ14, CQ15, CQ16, CQ17 (5 questions in total).

As it can be seen some competency questions falls into multiple categories since they pose requirements for more than one group. CQ grouping according to the Suárez-Figueroa et al. (2012) guidelines should be followed by validation and prioritization steps. However, these are highly user centered processes and due to time restrictions were not tackled.

The last step is to extract the terminology. In reflection to this thesis the terminology was extracted based on both: terms from competency questions and answers as well as the terminology used in assessment model. The terminology propositions can be seen in Table 28. Finally, otology requirements specification process outcomes are documented in ORSD (Table 29).

Table 28: Extracted terms

Terms from Competency Questions and Answers	Manufacturer, Material, Product, Location, ID, Type, Product Name, Material Name, Produced, Manufactured, Made Of, Life Span.
Terms from Assessment Model	Non-virgin input, Reusable output, Fixing factors, Edge standardization, Edge geometry, Morphology of Joints, Connection, Accessible, Not-Accessible, Accessible with causing no damage, Accessible with causing damage, Accessible with causing repairable damage, Knot, Linear, Point, Service, Half standardized, Made on Site, Pre-made, Accessory internal, Accessory external, Direct chemical, Direct integral, Direct integral with inserts, Direct integral with additional fixing devices, Filled with hard chemical, Filled with soft chemical, Open linear, Overlapping on one side, Symmetrical overlapping, Unsymmetrical overlapping, With insert on one side, With insert on two sides.

Table 29: Ontology Requirements Specification Document (ORSD)

Building Circularity Assessment Ontology (BCAO) requirements specification	
1	Purpose
	The purpose of Building Circularity Assessment Ontology (BCAO) is to provide all necessary product and material data for building's circularity assessment at early design stage according to selected assessment model.
2	Scope
	The ontology should be universal to enter the data for any manufacturer at any location. However, the scope limited to selected assessment model technical indicators and data that could be objectively entered by manufacturers.
3	Implementation language
	Ontology should be implemented in OWL.
4	Intended end users
	User1: Architect; User2: Manufacturer; User3: Project manager; User4: Owner;
5	Intended uses
	Use1: To search information about circularity indicators. Use2: To filter products according to user needs. Use3: To connect heterogenous data from various manufacturers for Circularity Assessment. Use4: To grow knowledge base for Circularity Assessment at early stage and update it.
6	Ontology requirements
	Functional requirements: groups of competency questions (a) Information about the product; (b) Assessment information; (c) Information about the material; (d) Information about the Company;
7	Pre-glossary of terms
	(a) Terms from Competency Questions and Answers; (b) Terms from Assessment Model;

5.8.2. Otology implementation

Ontology implementation stage follows the requirements identified in the previous stage and it is combined from three main processes: conceptualization, encoding and evaluation. Conceptualization refers to an activity of organizing and structuring the information obtained during the acquisition process, into meaningful models at the knowledge level according to the ontology requirements specification document (Suárez-Figueroa et al., 2012). BCAO ontology conceptualization was is based on the terminology extracted during requirement specification phase and presented in Figure 25.

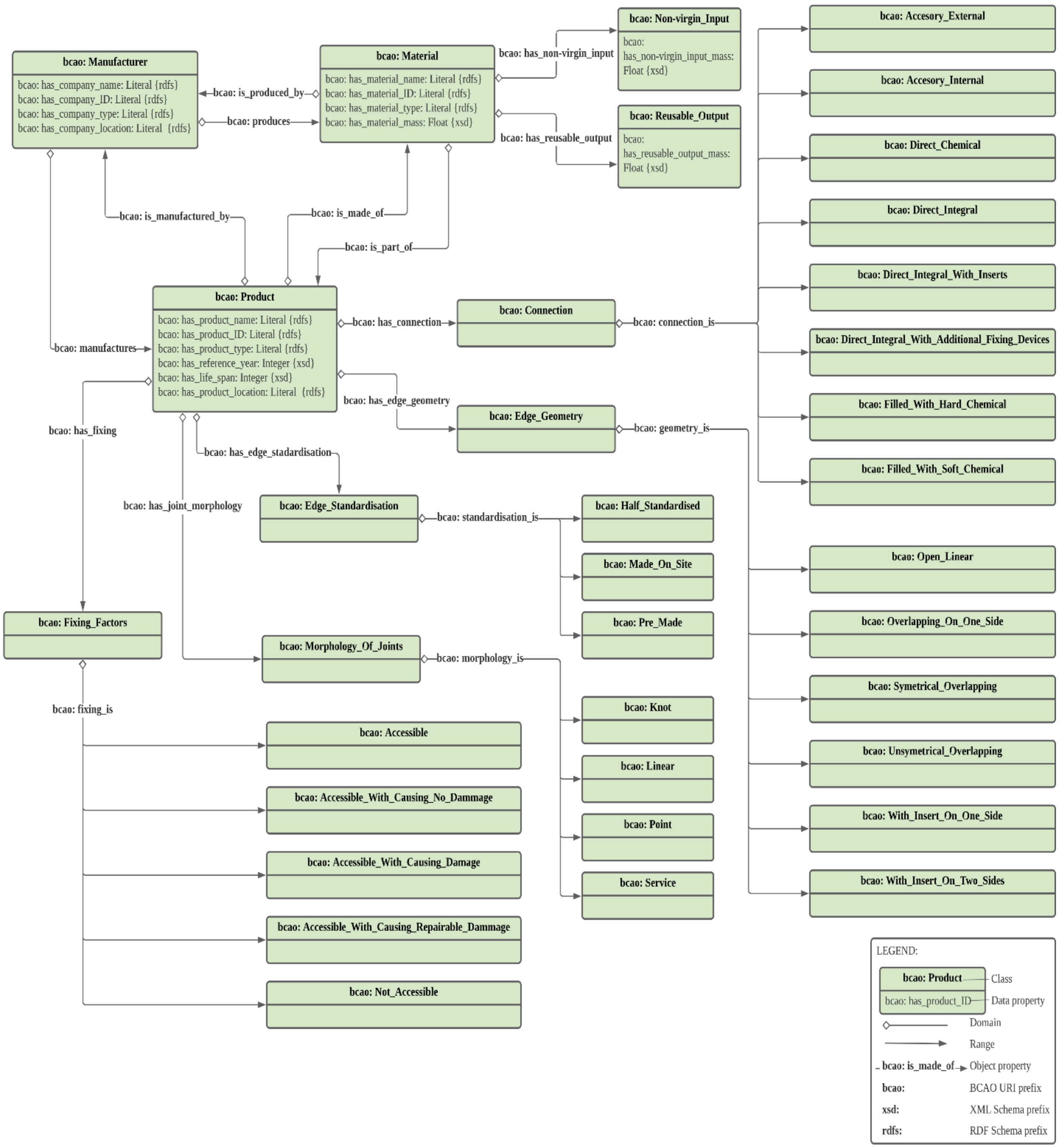


Figure 25: Conceptualization of BCAO ontology

Encoding is a process of transforming the concept into an ontology expressed in the chosen ontology implantation language (Espinoza-Arias et al., 2020). During the encoding process it is highly recommended to search for existing ontologies to be reused. This could be done for instance querying the ontology registries in LOV (*Linked Open Vocabularies (LOV)*, n.d.). In reflection to this thesis, the reusable ontology process was already performed during the literature review and possibly reusable ontologies identified and analyzed in chapter *"5.7.4 Ontology analysis"*.

Under further study it was found that Building Product Otology (BPO) could be reused to define the *Product* itself as it represents the same class as defined in BCAO. A couple of similar to BCAO object properties were identified in BPO ontology as well, for instance *bpo:is_part_of* or *bpo:consists_of*. However, these object properties are dedicated to defining product as an assembly rather than to specify the materials. Furthermore, Digital Construction Building Materials Ontology (DICBM) has a detailed definition of *Material* class including various components and layers. Still, even though DICBM has a lot of property definitions for material chemical, physical, mechanical characteristics, etc. specific product value definitions like material mass embedded was missing.

At the same time recently introduced Circular Economy ontologies CEO and CAMO as well includes reusable classes as *Product, Input, Output, Material*, etc. Though, the use of the CEO and CAMO classes and object properties did not really fit the purpose of technical circularity assessment. For instance, *ceo:input* is a subclass of *ceo:AffordsPostUseInput* which generally says if the material output could serve as an input for a post-use activity. However, in *bcao:has_non-virgin_input* the emphasis is on the non-virgin material embedded in the material used for the product. *Shema-org* (*Schema.Org*, n.d.) is one of the most used vocabularies to structure data on the Internet. Although, *Manufacturer* as a class was not found present in *Schema*, it could be as well defined as *schema:organization* coming together with other *Schema* properties like *shema:description* or *schema:location*. Furthermore, *Shema* holds some other relevant object properties like *schema:Manufacturer* which range is *schema:Organization*. Still, precision is missing while using *schema:Organization* to define *bcao: Manufacturer* as the class name itself already tells a lot for the user what kind of organization it is referred to as well as the properties naming in BCAO fits more to the case.

Finally, as it was defined in the ORSD scope section the ontology should be universal. Therefore, it is important to address the issue of various naming occurring in different organizations and even language barriers when considering separate countries. Here Building Smart Data Dictionary (bSDD) becomes very handy as it allows to recognize the different naming for same element. BPO ontology makes use of bSDD by introducing a class *bpo:classified_object*. The reusable classes for proposed BCAO ontology concept are illustrated in Figure 26.

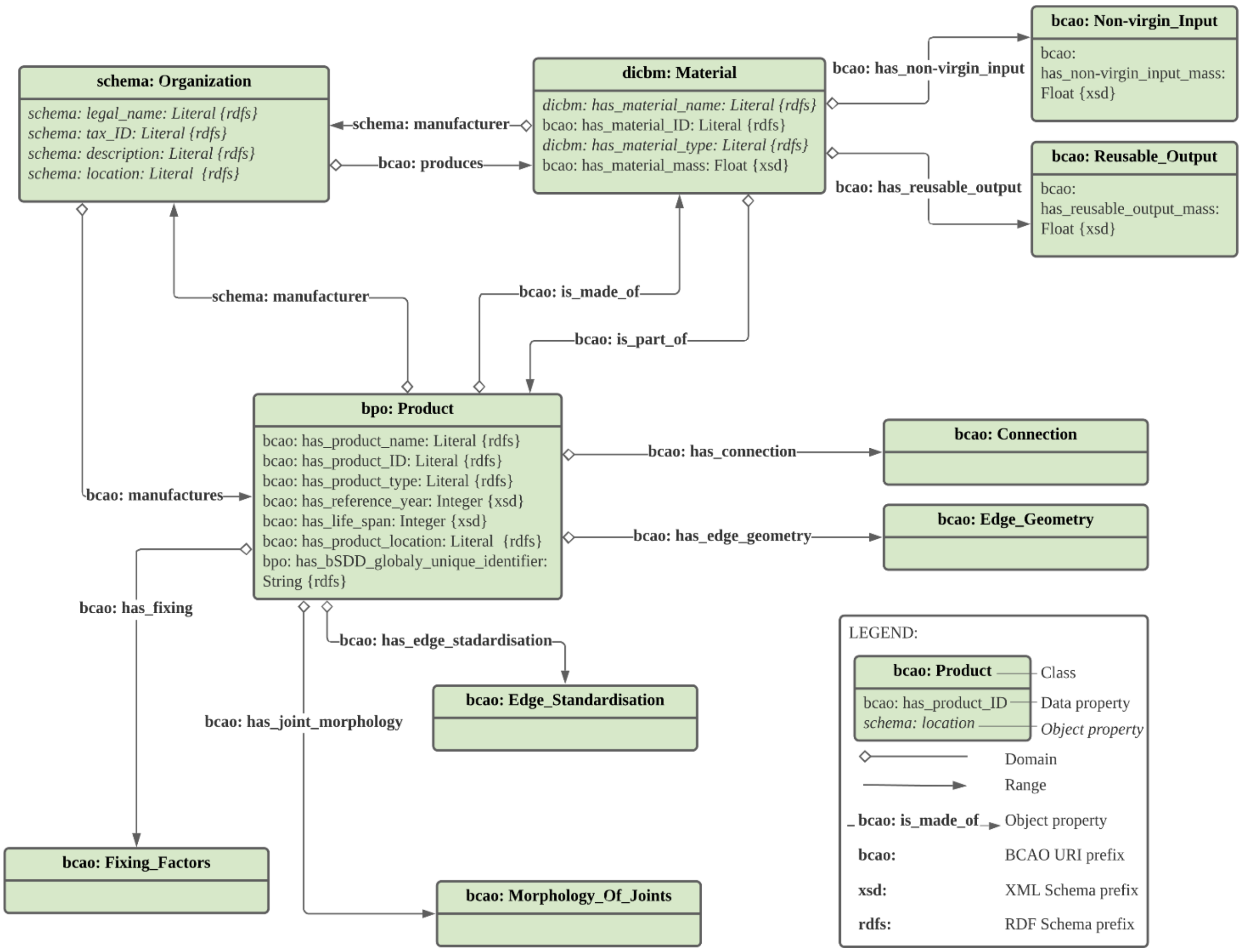


Figure 26: Reusable ontologies conceptualization for BCAO

Lastly, ontology evaluation process is an activity when technical quality of ontology is checked against the frame of reference (Suárez-Figueroa et al., 2012). Ontology can be evaluated based on various evaluation criteria like domain coverage, fit for purpose application, detection of bad practices, logical consistency, etc. (Espinoza-Arias et al., 2020). Automatic validators like OOPS! (*OOPS! - OntOlogy Pitfall Scanner!* n.d.) could be as well used. The practical implementation of the last two processes namely encoding and evaluation is presented further in chapters *"6. Prototype development"* and *"7. Validation"*.

5.9. System framework

Various gaps and limitations connected to the implementation of Circular Economy concept and building circularity assessment in the AEC industry were identified. Section (5.2) analyzed the identified gaps in relation to the interviews in order to narrow down the scope, support the desk research findings and provide input for the system analysis. Furthermore, based on that an analysis was conducted in section (5.5) to determine the potential mitigation of the identified gaps and limitations related to building's circularity assessment. In this section a general overview of the system framework which combines the findings from the previous analysis into systematic solution is provided. The proposed framework portrays a conceptual representation of the potential configuration for building's circularity assessment application. The framework is based on the previous analysis simulating the approach of how the various stakeholders (designers, project managers, manufacturers, contractors, etc.) will be involved in the process to make use of the circularity assessment web-application.

The system framework consists of three main layers namely: user layer, application layer and data layer (Figure 27). The building's circularity assessment can be achieved throughout the interaction between the mentioned layers. The user layer involves the users of the web-applications like designers or manufacturers. The main user of the *Assessment application* at the early design stage is considered to be the architect as he is making the first draft of the project. The role of the architect in the system framework is to provide the data from the model which further will be used for the assessment by the *Assessment application*. On the other side the manufacturers are responsible for providing the material/product data necessary for the assessment. As it was revealed during the research, the ways how manufacturer data currently is stored and shared varies significantly. Even though, there are means to convert and structure that data to a common knowledge base (the method further will be provided in chapter *"7. Validation"*) for the purpose of conceptual framework proposed in this thesis it is assumed that a separate web-application for entering manufacturer data (in Table 27 *Manufacturer application*) is employed. Subsequently, the manufacturer can utilize this web application for the purpose of sharing the required material and product data related to the technical requirements necessary to conduct the assessment.

Application layer combines two applications mentioned above, namely the *Assessment application* and *Manufacturer application*. The applications differ in their built-in features. For example, the *Manufacturer application* can encompass various features with the aim to: (1) facilitate the process of input and update the materials and products technical data; (2) Parse and convert different formats of data sources into triples and (3) export the converted data sources into different RDF serializations. On the other side, the *Assessment application* provides the following features: (1) Group building elements by type; (2) Visualize the imported model; (3) Suggest building elements based on specific filters; (4) Match building elements through IDs with elements stored in a database; (5) Calculate the building's circularity as a whole or MCI, PCI and SCI for materials, products, or systems and (6) provide suggestions to the building elements that have negative impact on the circularity score.

Finally, the data layer contains the manufacturer data converted and stored in separate triple stores which together represents the knowledge base were technical data related to materials and products from different manufacturers are linked and made available.

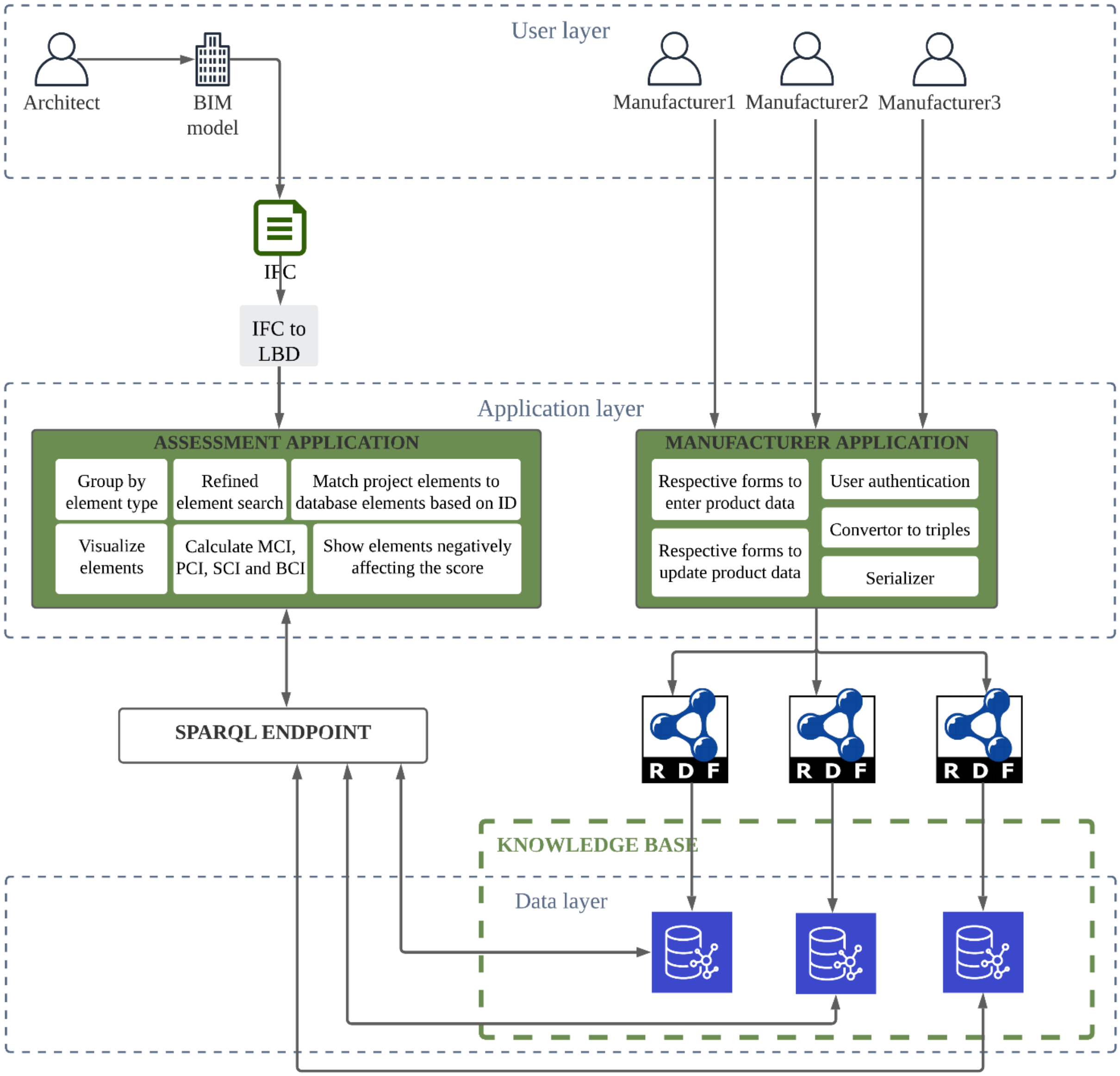


Figure 27: Proposed system framework for building's circularity assessment

Three different user scenarios were previously identified: two for the main user and one for the manufacturer. To ensure an understanding of the scenarios in reflection to the system framework a general overview of each scenario within the context of the system is presented, starting with scenario number 3 related to manufacturer, then scenario number 1 and 2 related to the main user.

Scenario number 3

This scenario is related to the manufacturer data more specifically the technical data required for the assessment. The manufacturer can be considered as the supplier of different building materials and products. For example, concrete, reinforcement, or prefabricated building elements. According to Bilal et al. (2017) the manufacturer can have their data stored in various ways like relational tables, spreadsheets, and XML files. As demonstrated in Figure 1, the manufacturer should employ a web application and utilize the built-in features to parse and convert the diverse data sources into homogeneous RDF triples, as well as export various RDF triple serializations such as XML, N3, or Turtle (Bilal et al., 2017). Moreover, the *Manufacturer application* should provide the option of manual input of the data through the use of specific templates, were user can fill the technical data related to the assessment for materials and products. As it is not the purpose of this research to propose a manufacturer application structure, further technical details were not explored. However, currently there are propositions for similar technical approach. For example, Ch. Frausing and M. Rasmussen suggested a web-application to visualize and enter manufacturer data related to sustainability which prototype can be found following the GitHub link in references (Frausing & Rasmussen, 2020).

The *Manufacturer application* will then upload the parsed data sources to the triple stores utilizing SPARQL queries. For instance, the SPARQL "update" query enables updating the triple store by inserting, deleting, loading, copying, and moving RDF graphs in a graph store (W3C, n.d.). Additionally, the SPARQL "CONSTRUCT" query enables creating new RDF statements from different triples (W3C, n.d.). It is important to mention that an ontology must be present in order to structure and convert the different data sources as well as to provide a structure for storing the triples (Niknam et al., 2019). This can be achieved by using the BCAO ontology proposed in the previous section.

Scenario number 1

This scenario is dedicated to the main user, utilizing the web-based application at early design phase. At this stage of early design, the main user will have a generic model with no specific information about the technical data required for the assessment. As demonstrated in Figure 1 the main user can convert an IFC to linked building data (LBD) in order to match the schema model with the database model. This can be done by the use of open tool proposed by Oraskari et al. (n.d.). The tool allows the conversion from IFC schema to Linked Building Data (LBD) by the use of various ontologies. One of the main benefits of the export is the usage of bSDD, meaning that the project elements can be easier recognized in the database. This export can be further uploaded to the assessment web application, in which it can be visualized, and the building elements can be grouped. Subsequently, the main user can utilize the drop-down menus available in the application to filter specific data required for the assessment such as the mass of virgin feedstock utilized in the elements production or the life span of the building elements. Here the application can give suggestions based on the applied filters by utilizing SPARQL queries to retrieve necessary data from the manufacturer knowledge base as described in scenario number 1. Additionally, the main user can select different building elements from the various suggestions and perform circularity assessment for the building as a whole or MCI, PCI and SCI for materials, products, or systems. This enables the user to assess his selection based on the suggestions provided and consider different building elements from several manufacturer to examine their effect on the building circularity score.

Scenario number 2

This scenario is as well related to the main user, utilizing the web-based application to assess the design, but at a more advanced stage of the project. As demonstrated in Figure 1 the main user can convert an IFC to linked building data (LBD), upload the export, visualize the model, and group building elements by type similar to scenario number 1. However, in this case the application should match the model elements with the products available in the database automatically. In order to perform the circularity assessment technical data related to materials and products should be available. As this scenario is dedicated for the more detailed design, according to Pauwels & Petrova, (2020) the manufacturer data can be provided in different ways such as: (1) Parametric BIM objects; (2) Utilizing plug-ins; and (3) Modeling using manufacturer specific BIM objects. However, there are limitations for such approach. For instance, the provided parametric objects are simplified version to meet architects' requirements, the difficulties to cope with the high number of different manufacturer plug-ins and the issues of modeling responsibilities and data needs replacing the generic BIM objects with Specific manufacturer BIM objects. In this case, based on the Table 27, the application can retrieve the necessary technical data that is not captured by the parametric BIM objects. Using SPARQL queries to retrieve the missing data needed for the assessment from the manufacturer knowledge base while utilizing Building Smart Data Dictionary (bSDD) and the provided IDs. Now correspondingly, the main user through the web-application can perform a circularity assessment for the building as a whole or MCI, PCI and SCI for materials, products, or systems.

To conclude, this conceptual system framework represented a general overview of the approach that can be utilized by manufacturers using a web-application to parse, convert and upload different data sources as an RDF triples to triple stores. In addition, the approach of the main user utilizing the assessment web-application based on two scenarios retrieving the needed technical data and performing the building circularity assessment is discussed. As indicated previously by Niknam et al., (2019) ontologies must be present to define the vocabularies and structure required to convert heterogenous data sources and provide a structure for storing the triples. During this research it became clear that the main gap for the circularity assessment lies in the difficulties while retrieving the data. Therefore, and for the purpose of this study, the defined system framework scope will be narrowed to further develop the BCAO ontology in order to provide the necessary vocabulary and structure to capture the required technical data for the assessment.

6. Prototype development

The conceptualization of circularity assessment system framework described in chapter *"6.9 System framework"* paved the way for identification of the most significant gap from the technical perspective in order to move forward to the system implementation in practice. As it was found during the desk research and interviews currently there are ways to implement most of the proposed framework as BIM modelling software is able to export IFC files, there is an existing tool to convert the IFC to LBD and even circularity assessment platforms like *Madaster* to perform the assessment. However, the assessment is impossible without the data and the existing lack in necessary information as well as data sharing and storing issues made the need for a common open data platform obvious.

Nevertheless, the way towards this type of solution for open data retrieval is complex and time demanding process. Ontologies were identified as a key element for a common data structure and could be named as a first step for platform development. Therefore, in this chapter the BCAO ontology concept proposed in chapter *"5.8 Ontology definition for product circularity"* is developed further and technically implemented in *Protégé* software.

6.1. Reusability of ontologies in practice

In chapter *"5.8.2 Ontology implementation"* several ontologies with potential for reusability were identified. Best practices always recommend reusing as many ontologies as possible while developing a new solution. Therefore, before starting the technical implementation of BCAO ontology in *Protégé* the previously found potentially reusable ontologies were imported to the software to explore the extensibility possibilities.

Building Product Ontology (BPO) showed a great potential to be extended for building circularity assessment as it contains the general description of building products and their assembly. However, when imported in *Protégé* software the latest ontology definition showed errors in some defined classes. Furthermore, proposed class hierarchy was not really comfortable to be reused as *bpo:Product* is a subclass of *bpo:Component* which itself is a superclass for two more classes *bpo:Assembly* and *bpo:Element*. According to the description *bpo:Product* is any item that can be offered by vendors or manufacturers and has to be clarified by one of other two classes namely *bpo:Element* (which defined an item that is not composed or cannot be composed of other components) or *bpo:Assembly*. BPO Assembly class is defined as a structure composed of at least two components, however here it is referred to components as parts rather than describing the materials. Of course, the individual components in the otology could be extended with additional properties for describing the materials, though in the case of building circularity assessment the component itself is not as important as the material it is made of. Furthermore, it would make additional complications when describing the disassembly factors as some of the factors refer to the product parts like fixings for example, meaning that the assembly should be extended further, while other factors should be described as separate classes. This would make the ontology quite complex and complicate the querying. Knowing that BPO ontology as well is still under development and ontology evolution is time consuming process the possibility to reuse this ontology in the future is not rejected as also many benefits like the use of bSDD or clearer product definition is offered by BPO. However, for the purpose of this study it was decided not to reuse the BPO ontology at this stage.

Similar considerations were made also while exploring the DICBM ontology in *Protégé*. Even though, DICBM has a very detailed description of various mechanical, chemical, physical properties, etc. this kind of expressiveness is seen redundant in reflection to this thesis research and would obscure the further validation process. DICBM ontology is dedicated to describing materials, therefore many other classes to define the *Product* itself and disassembly factors would have to be introduced, which would also complicate the hierarchy. Furthermore, some errors while loading DICBM ontology were observed as well. For instance, BFO (Basic Formal Ontology) could not be loaded.

The only ontologies found, which were dedicated for describing Circular Economy processes is CEO and CAMO. Even though, there were some potential in reusing several classes or object properties from CEO and CAMO, these ontologies were uncovered to be in the development process and loadable files were not provided. And as for the reusability of *Schema-org* offered classes and properties wile describing the *Organization* it was decided that for the clarity of the proposed BCAO ontology it would be more comprehensive to name the class *Manufacturer* as if necessary, further it could be extended with *Equivalent to* functionality.

In conclusion, for the purpose of clear understanding and easier validation it was decided to work on the BCAO ontology prototype without extending the currently available ontologies. However, the perspectives of reusable ontologies are seen and if during ontologies evolution some issues will be resolved they could be extended or reused to follow the purpose of BCAO ontology.

6.2. BCAO ontology definition in Protégé

Having the concept of the ontology defined the next step is to implement it technically. *Protégé* is one of the widest used open-source software for ontology creation and therefore, was chosen for the purpose of this research as well. The ontology development starts with the definition of ontology IRI (Internationalized Resource Identifier) which in this case was chosen to use GitHub repository (linmor-sys, 2020). The main web vocabulary prefixes *owl, rdf, rdfs, xml* and *xsd* are already present in *Protégé*, therefore only the created ontology *bcao* prefix is added.

The first step, while creating the ontology is to define the classes and sub-classes. Here the mapping from ontology conceptualization phase were used and hierarchy created as seen in Figure 28 (a). All the classes are the subclasses of the top-class *owl:Thing*. Further classes are created in order to define the *Product, Material, Manufacturer,* and factors necessary for circularity assessment. Subsequently, the classes are disjointed so the product could be defined correctly according to chosen assessment model. Further, the object properties are defined as seen in Figure 28 (b). Object properties are necessary to define the connection between two classes, which then completes the triple. The object properties similarly to classes are all sub properties of the *owl:topObjectProperty*. Object properties can have *Classes* defining the domain and range of the property or this can be defined by stating the restrictions. Furthermore, object properties can have various characteristics like *Functional, Transitive, Symmetric*, etc. which helps to make sure the reasoning is correct. For example, it would be fair to say that normally an end product would be manufactured by only one manufacturer, therefore this property can be set to *Functional*.

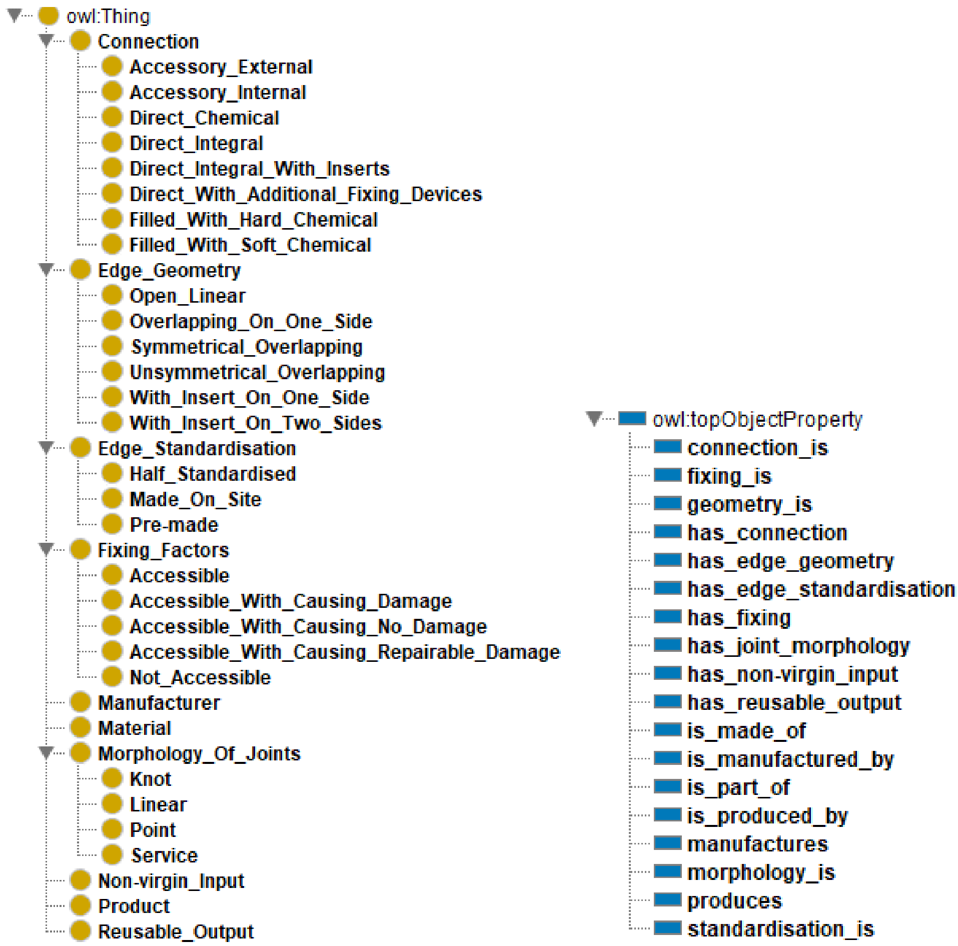


Figure 28: (a) BCAO class taxonomy; (b) BCAO object properties

Restrictions have shown to be really useful for the purpose of this thesis while defining the BCAO ontology. To make sure that the product will have the disassembly factors assigned correctly some restrictions were set. For example, there are five options to access fixings namely: accessible, accessible with causing damage, accessible with causing no damage, accessible with causing repairable damage or not accessible. Logically and according to the assessment model it is clear that only one option can be chosen. Therefore, here a restriction is set that the fixing accessibility is only one of the mentioned factors. The example of a restriction can be seen in Figure 29.

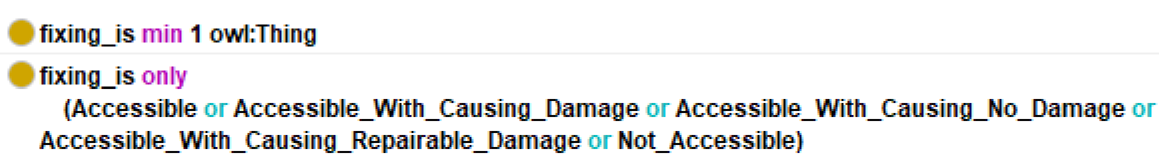
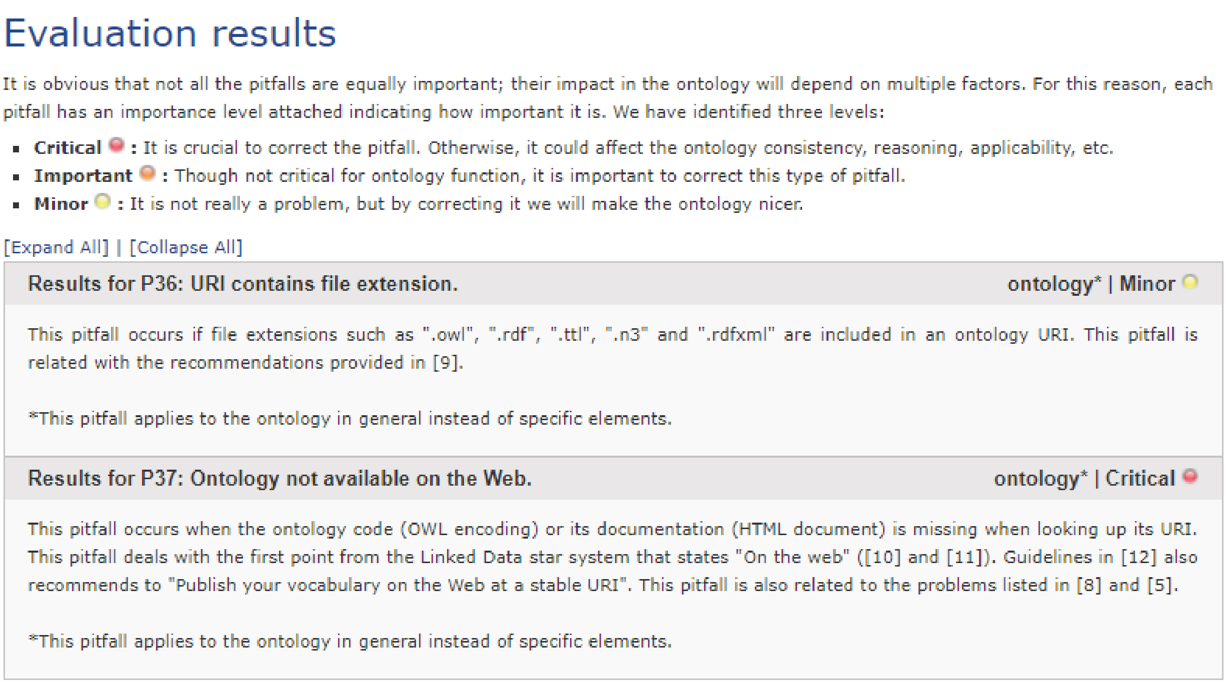


Figure 29: Restriction for fixing factors

Having all the classes, object properties and restrictions set, data properties are defined. Data properties are necessary to give specific information about the named classes. For example, non-virgin material input should be specified by giving the exact input mass. Data property allows to set the domain in this case being *bcao:Material* and range as a datatype (*rdf, rdfs, xsd*, etc.) or data range expression. To make sure no mistakes were done, while setting the domains, ranges or creating restrictions, the reasoner is invoked. There are several reasoners, which could be used in *Protégé*, however in this case an in-built reasoner HermiT 1.4.3.456 is used.

The created ontology can be saved in multiple formats, while in this case two formats were used namely OWL and TTL. *WebVowl* (*WebVOWL*, n.d.) ontology visualizer was used to inspect the ontology and double-check if all the classes and properties are connected correctly. Finally, ontology was loaded into the OOPS! (*OOPS! - OntOlogy Pitfall Scanner,* n.d.) to detect potential pitfalls. However, as it is seen in Figure 30 only two pitfalls were found. One of them is marked in red and considered critical, indicating that the ontology is not available on the Web. Though, ontology publishing is the third step in LOT methodology which is not implemented in this thesis.



Evaluation results

It is obvious that not all the pitfalls are equally important; their impact in the ontology will depend on multiple factors. For this reason, each pitfall has an importance level attached indicating how important it is. We have identified three levels:

- **Critical** : It is crucial to correct the pitfall. Otherwise, it could affect the ontology consistency, reasoning, applicability, etc.
- **Important** : Though not critical for ontology function, it is important to correct this type of pitfall.
- **Minor** : It is not really a problem, but by correcting it we will make the ontology nicer.

[Expand All] | [Collapse All]

Results for P36: URI contains file extension. ontology* | Minor

This pitfall occurs if file extensions such as ".owl", ".rdf", ".ttl", ".n3" and ".rdfxml" are included in an ontology URI. This pitfall is related with the recommendations provided in [9].

*This pitfall applies to the ontology in general instead of specific elements.

Results for P37: Ontology not available on the Web. ontology* | Critical

This pitfall occurs when the ontology code (OWL encoding) or its documentation (HTML document) is missing when looking up its URI. This pitfall deals with the first point from the Linked Data star system that states "On the web" ([10] and [11]). Guidelines in [12] also recommends to "Publish your vocabulary on the Web at a stable URI". This pitfall is also related to the problems listed in [8] and [5].

*This pitfall applies to the ontology in general instead of specific elements.

Figure 30: OOPS! Scanning results

7. Validation

This chapter deals with the validation of the prototype developed and described in the preceding section. The aim is to provide the basis for answering sub-question number four, by demonstrating the usability of BCAO ontology to facilitate the assessment of building's circularity at the early design stage. Consequently, BCAO ontology is utilized to structure the technical data needed for the assessment while ensuring the required vocabulary to align and query the data. To check the ability of BCAO to assist in the data structuring and query, a 3D generic model is employed to simulate scenario number one described in section "5.3 "and section "5.9". Various building elements data is presented as a tabular format to imitate the manufacturer data required for the assessment which later is converted to RDF data model. Additionally, a triple store was utilized to store and retrieve the necessary data for the assessment. Based on the retrieved data a circularity assessment for the selected 3D model is performed and a discussion for different selected suggestions is presented.

7.1. Case description

As described in scenario number one, the main user has a generic model for the preliminary early design which will be imported into the assessment application. Therefore, and for the purpose of this validation a 3D model was utilized as shown in Figure 31. The 3D model represents a small residential house with a gross floor area of 300 m². It consists of reinforced concrete external walls, internal partitions, doors, and windows. Appendix C represents the Bill of materials of the selected model.

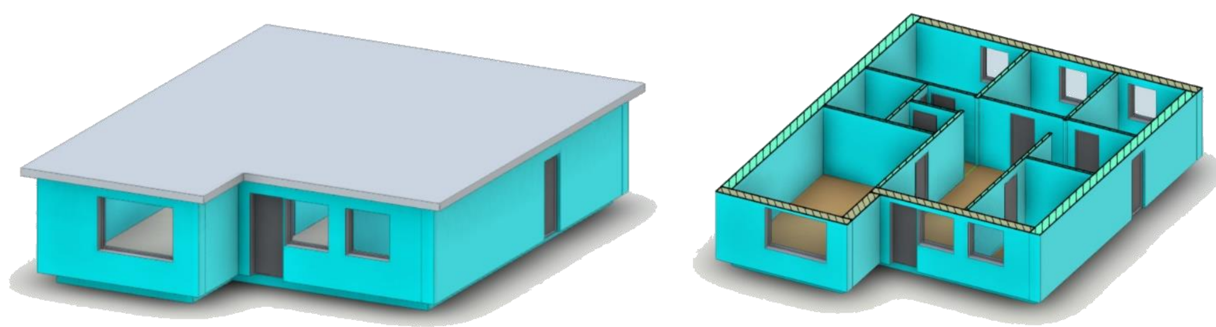


Figure 31: 3D model used for validation

The 3D model is used in the validation process simulating the approach that the main user will undertake to perform the assessment. As mentioned earlier, the scope of the validation is not to examine the entire system framework but to utilize BCAO to structure the technical data necessary for the assessment and provide the needed vocabulary to align, convert and query the data. Moreover, at early design phase the 3D model will be lacking the required technical data necessary for the assessment. Therefore, the needed information can be retrieved from the manufacturer database.

7.2. Employing manufacturer data

Manufacturer data is vital for the assessment. Therefore, at the early design stage this information must be retrieved. For the purpose of this research and to continue with the validation process, the technical manufacturer data regarding different building elements was captured in a tabular format as an *Excel* spreadsheet, see Appendix D. The spreadsheet serves as a demonstration of how the technical data can be structured and converted to RDF data model. This converted data then can be stored and queried. The aim of this approach is to demonstrate the ability of BCAO to provide the necessary structure for the required data as well to demonstrate the usability of BCAO for the alignment of the RDF schema with the spreadsheet data. *OpenRefine* was utilized for the purpose of alignment and converting the spreadsheet data into RDF triples. *OpenRefine* *"is a powerful tool for working with messy data: cleaning it; transforming it from one format into another; and extending it with web services and external data"* (OpenRefine, n.d.). The process of alignment using *OpenRefine* can be seen in Figure 32.

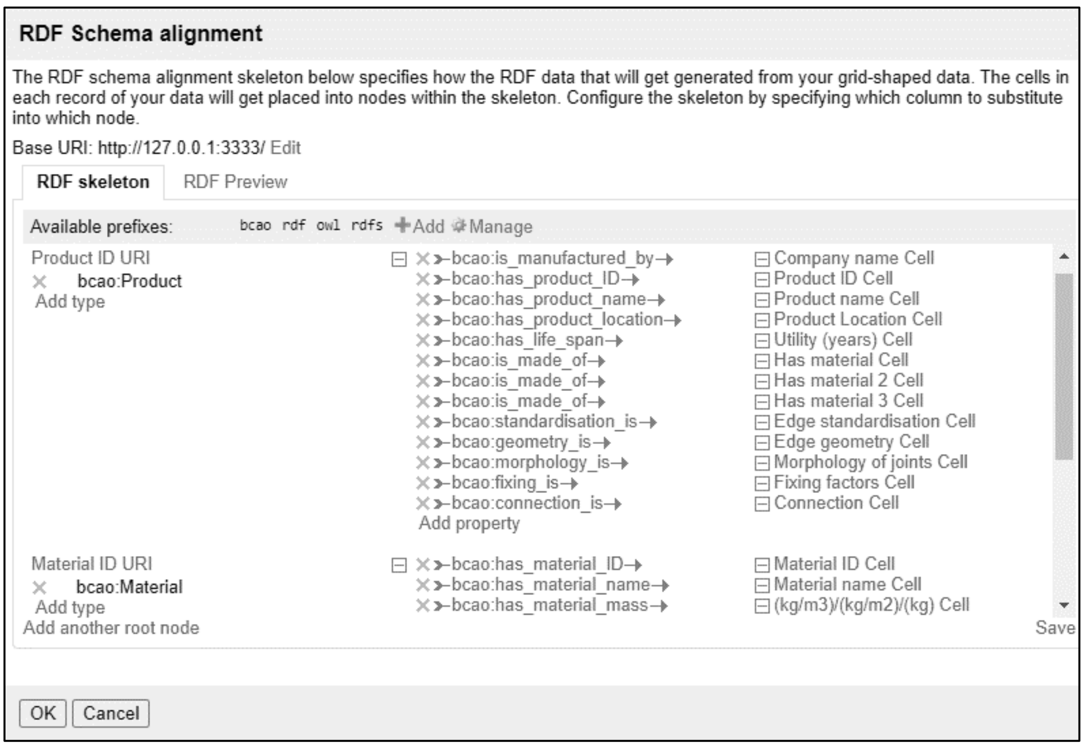


Figure 32: Converting spreadsheet data into RDF data model using OpenRefine

It can be noticed from Figure 32, that BCAO was imported to utilize the classes and object properties defined during the ontology development phase. For instance, *bcao:Product* class can be aligned with the respective data related to the product ID using *object property has_product_ID*. Similarly, each data in the spreadsheet can be aligned utilizing the predefined *object properties*. Figure 33 demonstrates the *bcao:Poduct, bcao:Manufacturer, bcao:Material* classes aligned with their respective data imported from the spreadsheet. Furthermore, the interlinks between the triples can be seen as for instance, *bcao:Product* triple has an object property *bcao:is_made_of* where the IDs of the materials which the product is made of can be observed.

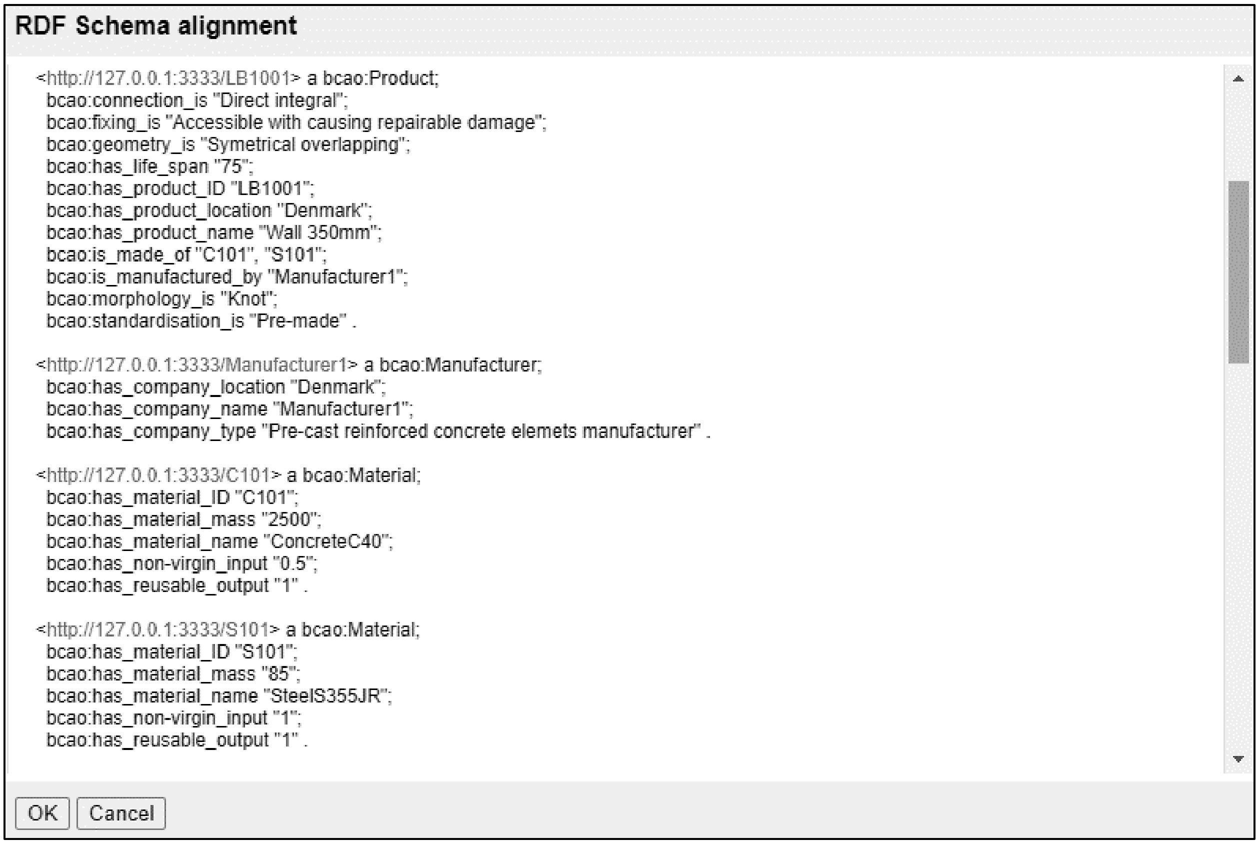


Figure 33: Spreadsheet data and RDF Shema alignment using OpenRefine

The resulted RDF schema can be exported into different RDF serializations such as *Turtle* or *XML*. According to the system framework the newly converted dataset should be stored in a triple store. This enables the assessment application to query the data required for the assessment. Consequently, *Apache Jena Fuseki* triple store was chosen for that purpose to host the converted dataset. The tool comes as a web-application providing a user interface to store the dataset and is equipped with SPARQL 1.1 for querying and updating (Apache Jena Fuseki, n.d.). This will be further used to illustrate the ability to query the relevant data for the assessment.

7.3. Querying the data

By the use of *OpenRefine* the BCAO ontology was utilized to structure and convert the data required for the assessment. Further, the dataset stored in the *Fuseki* triple store is queried for the necessary data to perform the assessment. With reference to the system framework and user scenario number one the main user should be able utilize the assessment application to provide suggestions of the available building elements from the manufacturer knowledge base. The main user should employ the drop-down menus to retrieve filtered suggestions. For example, the application should allow to specify the life span of an external wall and based on such filter retrieve the available suggestions to choose from. To be able to perform that the assessment application should have a set of *SPARQL SELECT* queries to retrieve the required data. As part of the validation, and to imitate the application role, a set of SPARQL queries will be tested to check if the required data can be retrieved from the manufacturer data converted in the previous section.

For a clear demonstration of the above-mentioned example related to the recommendation retrieval for external walls with a 75 years of utility life an illustration of the *SPARQL SELECT* queries that can be encoded within the assessment application for this specific scenario will be presented. Figure 34 shows the SPARQL query that can be encoded within the application to bring back suggestions for external walls with utility factor equal to 75 years. It can be noticed that the *bcao* is declared as a prefix to present the namespace referred with the URI <https://github.com/linmor-sys/BCAO.owl#>, along other prefixes such as *owl, rdf, xml, xsd* and *rdfs*. This prefix will be utilized to use the BCAO ontology to query the necessary data. The introduced *SPARQL* query employs the *SELECT* form *"which Returns all, or a subset of, the variables bound in a query pattern match"* (W3C, n.d.).The statements between the curly brackets begins with assigning a variable for the external walls "*?External_Walls*". This variable will hold all the matching criteria which is *bcao:has_life_span equals to "75"*. Further, for each external wall that matches the mentioned criteria the Name, ID and material can be retrieved by assigning different variables *(?P_Name, ?P_ID, ?M_ID*) as well as using (*bcao:has_product_name, bcao:has_product_ID, bcao:is_made_of*) object properties. Moreover, another variable "*M_Subject*" was assigned to retrieve the name of the materials incorporated in that building element using *bcao:has_material_name*.

The query will retrieve different suggestions to the main user from the manufacturer knowledge base. Figure 35 demonstrates the query results grouped by product ID, product name and material name. It can be noticed that nine results which represents four walls that matches the filter criteria were retrieved, three reinforced concrete walls and one reinforced sandwich wall. From the results the main user can have a preliminary overview of the available data for the external walls. For instance, based on the outcomes demonstrated in Figure 35 the main user can choose any external wall from the suggestions. Subsequently, the application can query the relevant data for assessment for the specific selection. Figure 36 demonstrates the query that can be encoded within the application to retrieve the relevant information from the assessment and provide better insight for the main user about their selection. This query consists of three parts: First, query statements related to product information such as name, location, utility factor, manufacturer name, and DFD factors; Second, query statements related to the manufacturer such as name, location, and type; Third, query statements related to the material information such as name, ID, mass, percentage by mass of non-virgin input and percentage by mass of reusable output. Moreover, with reference to the 3D model shown in Figure 31, using the same SPARQL queries the main user can have different suggestions for internal walls, doors, and windows. In addition, the assessment related information can be queried to perform the building's circularity assessment.

```
prefix bcao:  <https://github.com/linmor-sys/BCAO.owl#>
prefix rdf:   <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix owl:   <http://www.w3.org/2002/07/owl#>
prefix xml:   <http://www.w3.org/XML/1998/namespace>
prefix xsd:   <http://www.w3.org/2001/XMLSchema#>
prefix rdfs:  <http://www.w3.org/2000/01/rdf-schema#>


SELECT
        *
WHERE

{

  ?External_Walls     bcao:has_life_span  "75";
                      bcao:has_product_name  ?P_Name;
                      bcao:has_product_ID   ?P_ID;
                      bcao:is_made_of     ?M_ID.
  ?M_Subject          bcao:has_material_ID   ?M_ID;
                      bcao:has_material_name ?M_Name





}
  group by  ?P_ID  ?P_Name ?M_Name
ORDER BY ASC (?P_ID )
```

Figure 34: SPARQL query for retrieving the external walls with utility of 75 years

QUERY RESULTS

Table | Raw Response

Showing 1 to 9 of 9 entries

Search: Show All entries

	P_ID	P_Name	M_Name
1	"LB1001"	"Wall 350mm"	"ConcreteC40"
2	"LB1001"	"Wall 350mm"	"SteelS355JR"
3	"LB1002"	"Wall 350mm"	"ConcreteC35"
4	"LB1002"	"Wall 350mm"	"SteelS355JR"
5	"LB1003"	"Wall 350mm"	"ConcreteC40"
6	"LB1003"	"Wall 350mm"	"SteelS255JR"
7	"LB1006"	"SandwichWall 350mm"	"Brick 240x70x112"
8	"LB1006"	"SandwichWall 350mm"	"ConcreteC40"
9	"LB1006"	"SandwichWall 350mm"	"SteelS355JR"

Showing 1 to 9 of 9 entries

Figure 35: SPARQL query results showing the external walls suggestions

```
prefix bcao:  <https://github.com/linmor-sys/BCAO.owl#>
prefix rdf:   <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
prefix owl:   <http://www.w3.org/2002/07/owl#>
prefix xml:   <http://www.w3.org/XML/1998/namespace>
prefix xsd:   <http://www.w3.org/2001/XMLSchema#>
prefix rdfs:  <http://www.w3.org/2000/01/rdf-schema#>

SELECT ?P_Name ?P_Location ?Company_Name ?P_Connection ?P_Fixings ?P_Geometry ?P_Morophology
       ?P_Standardization ?M_ID ?M_Name ?M_Mass ?M_Input ?M_Output

WHERE

{
  #Product_Query
 ?P_subject             bcao:has_product_ID                 "LB1001";
                        bcao:has_product_name               ?P_Name;
                        bcao:has_product_location           ?P_Location;
                        bcao:has_life_span                  ?Life_Span;
                        bcao:connection_is                  ?P_Connection;
                        bcao:fixing_is                      ?P_Fixings;
                        bcao:geometry_is                    ?P_Geometry;
                        bcao:morphology_is                  ?P_Morophology;
                        bcao:standardisation_is             ?P_Standardization;
                        bcao:is_manufactured_by             ?Company_Name.
  #Manufacturer_Query
 ?Company_Subject       bcao:has_company_name               ?Company_Name;
                        bcao:has_company_location           ?C_Location;
                        bcao:has_company_type               ?C_Type.

  #Material_Query
 ?P_subject             bcao:is_made_of                     ?M_ID.
 ?M_Subject             bcao:has_material_ID                ?M_ID;
                        bcao:has_material_name              ?M_Name;
                        bcao:has_material_mass              ?M_Mass;
                        bcao:has_non-virgin_input           ?M_Input;
                        bcao:has_reusable_output            ?M_Output.
}
```

Figure 36:SPARQL query for retrieving the assessment relevant data

QUERY RESULTS

Table | Raw Response

Showing 1 to 2 of 2 entries

Search: Show All entries

	P_Name	P_Location	Company_Nam	P_Conne	P_Fixings	P_Geometry	P_Morophc	P_Standardiz	M_ID	M_Name	M_Mass	M_Input	M_Output
1	"Wall 350mm"	"Denmark"	"Manufacturer1"	"Direct integral"	"Accessible with causing repairable damage"	"Symetrical overlapping"	"Knot"	"Pre-made"	"C101"	"ConcreteC40"	"2500.0"	"0.5"	"1.0"
2	"Wall 350mm"	"Denmark"	"Manufacturer1"	"Direct integral"	"Accessible with causing repairable damage"	"Symetrical overlapping"	"Knot"	"Pre-made"	"S101"	"SteelS355JR"	"85.0"	"1.0"	"1.0"

Showing 1 to 2 of 2 entries

Figure 37:SPARQL query results showing the assessment relevant data

7.4. Model assessment

This section presents the building's circularity assessment process with the reference to scenario number one. The assessment is based on the chosen assessment models described in section "5.5.7" namely, the material circularity indicator developed by EMF & Granta Design (2015) and the building circularity indicator developed by Verberne (2016). Moreover, the 3D model presented earlier in this chapter is assessed based on main user selections and demonstrates how the selection from the different suggestions related to the various building elements will affect the circularity score. The assessment will begin first with the calculation of the MCI for different building elements selected. Second, calculation of the PCI with relation to the DFD factors. Third, calculation of the SCI for each building layer under study, which in this case are the structural layer and the space layer. Finally, the calculation of the building's circularity indicator. In order to demonstrate the ability of the main user to adjust the material and building element utilized in their design at the early stage, an alternative building element selection is made and the new BCI is calculated.

7.4.1. Material circularity indicator

With respect to scenario number one the main user will select different building elements related to their design from the provided suggestions. In this case the 3D model utilized for the validation purposes serves as a reference to the main user for building element selection. According to Appendix C, the bill of material for the 3D model consists of six external walls (two reinforced concrete walls and two reinforced sandwich walls), nine internal concrete walls, eight doors and six windows. The main user should utilize the drop-down menus within the application to set filters in order to narrow down the suggestions retrieved from the manufacturer database. For example, in relation to the external walls the main user can filter for utility life equal to 75 years. Similarly, for internal walls can set the filter to retrieve concrete walls with utility life equal to 20 years. In the same fashion, filters for doors and windows with utility factor of 20 years. The encoded SPARQL queries illustrated in Figure 34 will retrieve different suggestions based on the filters. The main user can choose from the suggestions and further the SPARQL query illustrated in Figure 36 can retrieve more information for the selected building element. In this case the main user can chose the best option from the different candidates.

The ability to query the relevant data for the assessment for various building elements should enable the application to carry out the assessment, starting with the MCI. Table 30 demonstrates a part of the query results for the selected building elements encompassing the data required for MCI calculation. Equation 1 related to the calculation of MCI will be used to start with the assessment. A simplified version of this equation will be utilized for the purpose of this validation. For instance, the fraction of feedstock from reused (F_{U}) and recycled (F_{R}) will be referred as the *non-virgin input*. Similarly, the fraction of mass of the product that can be reused (C_{U}) at its EOL, and fraction of mass of the product that can be recycled (C_{R}) at its EOL will be referred as the *reusable-output*. Moreover, the material use intensity will not be considered in the calculation of the utility factor (X) as this information is difficult to obtain. In addition, the life span of the product will be assumed to be equal to building layer it belongs to.

Table 30: Summary of the query results for the selected building elements encompassing the data required for MCI calculation

	Material	Mass	Non-virgin input	Reusable output
External concrete wall			*52%*	*100%*
	Concrete	2500 (Kg/m3)	50%	100%
	Reinforcement	85 (Kg/m3)	100%	100%
External sandwich wall			*65%*	*90%*
	Concrete	2500 (Kg/m3)	50%	90%
	Reinforcement	85 (Kg/m3)	100%	100%
	Brick	2000 (Kg/m3)	100%	100%
Internal concrete wall			*80%*	*49%*
	Concrete	2500(Kg/m3)	80%	50%
	Reinforcement	85 (Kg/m3)	80%	0%
Door			*100%*	*100%*
	Wood	50 kg	100%	100%
	Wood	25 kg	100%	100%
Window			*100%*	*73%*
	Glass	30 kg	100%	80%
	Metal	15 kg	100%	50%

Based on the data shown in Table 30, The application can calculate the total product mass utilizing the volume of each element provided by the 3D model. Similarly, the average non-virgin input and average reusable-output can be determined. Utilizing the simplified version of Equation 1 MCI for each building element selected can be calculated. The following is a demonstration example for the external concrete wall MCI calculation.

$$MCI = \max\,(0, (1 - LFI * F(X)))$$

Where:

$$V = 1 - (Non\ virgin\ input) = 1 - 0.52 = 0.48$$

$$W = 1 - (Reusable\ Output) = 1 - 1 = 0$$

$$LFI = \frac{V+W}{2M} = \frac{48+0}{200} = 0.24$$

$$Utility\ factor\ (X) = \frac{L}{Lavg} = \frac{75}{75} = 1$$

$$F(x) = \frac{a}{X} = \frac{0.9}{1} = 0.9$$

$$MCI = (1 - 0.24 * 0.9) = 0.784$$

Moreover, the MCI for the remaining building elements can be calculated with the same approach using the simplified Equation 1 as shown in Table 31.

Table 31: Summary of MCI calculated for selected building elements

Building element	External concrete wall	External sandwich wall	Internal concrete wall	Doors	Windows
MCI	0.784	0.7975	0.6805	1	0.8785

7.4.2. Product circularity indicator

To calculate the products circularity indicator the DFD factors established by (Durmisevic Elma, 2006) can be utilized using equation (3). Different DFD factors can affect the reusability of the product at its EOL. In section "5.5.7" several DFD factors were chosen related to product geometry and connection. According to Durmisevic Elma (2006) each DFD aspect has its determining factor, which ranges between "0" being difficult to disassemble to "1" being easy to disassemble. Table 32 demonstrates the DFD aspects, sub aspects and their respective determining factors.

Table 32: DFD aspects, sub-aspect and respective determining factors. Adapted from (Durmisevic Elma, 2006)

DFD aspects	DFD sub-aspects	Factors
Edge standardization	Pre-made geometry	1
	Half standardized geometry	0.5
	Geometry made on the construction site	0.1
Edge geometry	Open linear	1
	Symmetrical overlapping	0.8
	Overlapping on one side	0.7
	Unsymmetrical overlapping	0.4
	With insert on one side	0.2
	With insert on two sides	0.1
Morphology of joints	Knot	1
	Point	0.8
	Linear	0.6
	Service	0.1
Fixing factors	Accessible	1
	Accessible with causing no damage	0.8
	Accessible with causing repairable damage	0.6
	Accessible with causing damage	0.4
	Not accessible	0.1

Connection	Accessory external	1
	Direct integral with additional fixing devices	0.8
	Direct integral with inserts	0.6
	Direct integral	0.5
	Accessory internal	0.4
	Filled with soft chemical	0.2
	Filled with hard chemical	0.1
	Direct chemical	0.1

Furthermore, the *SPARQL* query shown in Figure 36 can retrieve the relevant DFD factors necessary for the PCI calculation. Table 33 represents a part of the query showing the DFD factors related to the external reinforced concrete wall along with its respective determining factor.

Table 33: Part of the query results showing the DFD factors related to the external reinforced concrete wall

	Edge standardization	**Edge geometry**	**Morphology of joints**	**Fixing factors**	**connections**
External concrete wall	Pre-made	Symmetrical overlapping	Knot	Accessible causing repairable damage	Direct integral
	1	0.8	1	0.6	0.5

Utilizing Equation 3 the PCI can be calculated for the external concrete wall as per the following.

$$\mathrm{PCI_p} = \frac{1}{\mathrm{Fd}} \sum_{i=1}^{n} \mathrm{MCI_p} \cdot \mathrm{F_i}$$

Where:

$$\sum_{i=1}^{n} \mathrm{MCI_p} \cdot \mathrm{F_i} = (0.784 * 1) + (0.784 * 0.8) + (0.784 * 1) + (0.784 * 0.6) + (0.784 * 0.5) = 3.057$$

$$\mathrm{Fd} = \sum_{i=1}^{n} \mathrm{F_i} = 5$$

$$\mathrm{PCI} = \frac{1}{5} * 3.0576 = 0.611$$

Moreover, the PCI for the remaining building elements can be calculated with the same approach using the Equation 3 as shown in Table 34.

Table 34: Summary of PCI calculated for selected building elements

Building element	External concrete wall	External sandwich wall	Internal concrete wall	Doors	Windows
PCI	0.6115	0.653	0.340	0.84	0.720

7.4.3. System circularity indicator

To calculate the SCI, the building element should be categorized relevant to each building layer they belong to. To facilitate the validation, two layers were placed understudy namely, the structural layer and space layer. The structural layer includes the external walls (reinforced concrete and reinforced sandwich walls). Subsequently, the space layer includes (internal walls, doors, and windows). Equation 5 can be utilized to calculate the practical SCI. The practical SCI was chosen as the interfaces and connection between the products are important (Verberne, 2016). The following is a demonstration example for the SCI calculation based on the information provided in Table 35.

Table 35: Building elements categorized based on the building layer, with the total mass and PCI data provided

Building element	Layer	Total Mass	PCI
External concrete wall	Structural	49451.05	0.611
External sandwich wall	Structural	38232.15	0.653
Internal concrete wall	Space	21973.5	0.340
Doors	Space	600	0.84
Windows	Space	270	0.720

According to Equation 5,

$$\mathrm{SCI(structural)} = \frac{1}{Ws}\sum_{i=1}^{n} \mathrm{PCI} * \mathrm{W}$$

Where:

$$\sum_{i=1}^{n} \mathrm{PCI} * \mathrm{W} = (0.6115 * 49451.05) + (0.653 * 38232.15) = 55242.22$$

$$Ws = 49451.05 + 38232.15 = 87683.2$$

$$\mathrm{SCI(structural)} = \frac{1}{Ws}\sum_{i=1}^{n} \mathrm{PCI} * \mathrm{W} = \frac{1}{87683.2} * 55242.22 = 0.63$$

Moreover, the SCI for the Space layer can be calculated with the same approach Equation 5 in which results with, $\mathrm{SCI(Space)} = 0.357$

7.4.4. Building circularity indicator

To calculate the BCI, the SCI for each building layer calculated previously should be assigned a weight factor known as the level of importance related to that layer. Section "5.5.2" Table 20 demonstrated the building layers with their respective level of importance. In this study two layers were examined the structural and space layers. Table 36represents the data required to conduct the BCI utilizing Equation 7.

Table 36: Data required to conduct the BCI

Building layer	Level of importance	SCI
Structural	0.2	0.630
Space	0.9	0.357

According to Equation 7,

$$BCI(p) = \frac{1}{LK}\sum_{k=1}^{n} SCI(p)k \cdot LKk$$

Where:

$$\sum_{k=1}^{n} SCI(p)k \cdot LKk = (0.2 * 0.630) + (0.9 * 0.357) = 0.448$$

$$LK = 0.2 + 0.9 = 1.1$$

$$BCI(p)\frac{1}{LK}\sum_{k=1}^{n} SCI(p)k \cdot LKk \ = \frac{1}{1.1} * 0.448 = 0.407$$

In the light of the assessment results, the main user will have a better understanding of the building elements selection and should be able to decide whether the results are satisfactory in terms of circularity. In this case based on the main user selections the overall BCI score was equal to 0.4480. With accordance to the main user design criteria relating to circularity, it may be satisfactory or needed to be enhanced. If the main user will require a better circularity score for their design, different building elements can be selected again from the provided suggestions. This iterative process will allow the main user to select different materials and products and decide based on the assessment results comparison.

7.4.5. Alternative selection

In this case the main user would like to enhance the BCI score therefore, different building elements can be selected. Once again, the main user can employ the same filters described before to retrieve building elements suggestions. To facilitate the process and have a better demonstration, the main user will choose to change the internal concrete walls with internal gypsum partitions. The assessment will be conducted in the same manner, additionally, the previous results for the other building elements will be utilized and the new MCI, PCI, SCI and BCI will be calculated. Table 37, Table 38, Table 39 and Table 40 represents a summary of the data required to calculate the new assessment score.

Table 37: Data required to calculate the MCI (internal gypsum partition wall)

	Material	Mass	Non-virgin input	Reusable output
Internal gypsum partition	Gypsum	9.2 (Kg/m²)	*100%*	*80%*
			100%	80%
	Metal frame	50 Kg	100%	80%

Based on the data provided in Table 37, the MCI (internal gypsum partition) can be calculated using Equation 1which equals to: MCI (internal gypsum wall) = 0.91

Table 38: Data required to calculate the PCI (internal gypsum partition wall)

	Edge standardization	Edge geometry	Morphology of joints	Fixing factors	connections
Internal gypsum partition	Pre-made	Symmetrical overlapping	Knot	Accessible causing no damage	Filled with soft chemical
	1	0.8	1	0.8	0.2

Based on the data provided in Table 38, the PCI (internal gypsum partition) can be calculated using The calculation of product circularity indicator, (Verberne, 2016, p.68) which equals to: PCI (internal gypsum wall) = 0.691

Table 39: Complementary data required to calculate SCI_{new} (Space layer)

Building element	Layer	Total Mass	PCI
Internal Gypsum partitions	Space	764.36	0.691

Based on the previous results and the data provided in Table 39, the SCI_{new} (Space layer) can be calculated using Equation 5 which equals to: SCI_{new} (Space) = 0.749

Table 40: Complementary data required to calculate BCI_{new}

Building layer	Level of importance	SCI
Space	0.9	0.749

Based on the previous results and the data provided in Table 40, the BCI_{new} can be calculated using Equation 7 which equals to: BCI_{new} = 0.728

7.5. Comparing the results

It can be noticed that the MCI (internal concrete walls) which equals to 0.68, compared to 0.91 for the MCI (internal gypsum partitions). This difference in MCI for both building elements is related to the difference in the material composition, amount of virgin feedstock used and the reusable output at its' EOL. For example, gypsum board is more likely to be reused or recycled for the same purpose at its EOL compared with concrete that it is most likely to be downcycled for other purposes.

Moreover, to compare the PCI (internal concrete walls) which equals to 0.340 compared to 0.691 for the PCI (internal gypsum partitions). This difference in PCI for both building elements is related to the difference in the interfaces and connection behavior of both building elements with its surrounding elements. For example, the edge standardization in premade in the case of internal gypsum partition, which enables the disassembly causing no damage, compared to a made-on site edge standardization in the case of internal concrete walls, which can cause a possible damage when disassembled.

The differences in both MCI and PCI will affect the SCI (Space layer) as well, it can be noticed that the SCI for the first building element selection equals to 0.357 compared to 0.749 caused by the alternative internal walls selection. Additionally, there was no change for the SCI (structural layer) as the change in the selection belongs only to the space layer.

As for the BCI, it is noticeable the difference in the score between the first and alternative selections. The BCI score for first selection equals to 0.407 compared to 0.728 for the BCI_{new} caused by the alternative internal walls selection.

Having the assessment results for the different selections, the main user can compare between the selected building elements and their respective MCI, PCI, SCI and BCI results. Based on that comparison the main user can decide what building element will satisfy their design criteria.

7.6. Chapter conclusion

To conclude this chapter dealt with the validation of the prototype developed in chapter "*6. Prototype development*". The validation was divided into three steps namely, use case description, prototype testing and results analysis. For the first step, a 3D model was utilized to demonstrate how the main user can conduct the circularity assessment for their design. Additionally, scenario number one was chosen, where the main user will have the ability to choose from different suggestions based on specified filters. For the second step, the BCAO ontology was tested to demonstrate the ability of its utilization with respect to technical data structuring. In addition, the use of the BCAO vocabulary to align and convert manufacturer data, as well as the ability to query the relevant technical data from the manufacturer knowledge base. For the third step, utilizing BCAO ontology enabled to proceed with simulation the assessment application role and calculate the MCI, PCI, SCI and BCI for two options selected by the main user.

Furthermore, with respect to the three evaluation criteria mentioned in section "2.4.5" namely, (1) accuracy, (2) usability, and (3) assessment needs. First, the accuracy was examined with relation to the ability to retrieve the needed data for the assessment from the converted manufacturer data. Generalization cannot be made on the accuracy, as the tested sample was not wide enough. However, with relation to this research, using BCAO, the manufacturer data related to the assessment was structured and able to be queried with the necessary input to conduct the assessment. Second, the usability of the queried data was examined by simulating a case which is the 3D model utilized, where the main user will assess their design in terms of circularity by comparing different circularity assessment scores from different selected suggestions. Finally, the assessment needs, as the ontology development is an iterative process, in which with each iteration enhancement can be made to the ontology to catchup with changing demands of the assessment models. With regards to this validation scope, the first iteration demonstrated the capability of BCAO to provide a suitable structure for the assessment data as well as to provide vocabulary in order to align and convert the manufacturer data and enable the query of the relevant data for the assessment.

8. Discussion

During this research, a number of technology related gaps were found in order to perform a successful building circularity assessment at the early design stage. These gaps were categorized in six groups namely BIM environment gaps, assessment gaps, circularity assessment tool gaps, material passport gaps, existing databases gaps and data management gaps in AEC industry. The identified gaps showed that currently there are many issues preventing the implementation of a circular building. Starting with the assessment itself it became clear that at the moment there is no universal assessment model present and different models place emphasis on diverse circularity aspects. As the main goal of Circular Economy is closing the resource loops it is crucial to consider the building elements reusability for a second life. However, the study showed that disassembly of buildings and their components at the end of their life phase is not commonly considered during the design. This as well led to the related gaps in scholar proposed assessment models. To close this gap a combination of several authors assessment propositions including Ellen MacArthur Foundation & Granta Design (2015), Verberne (2016) and Durmisevic Elma (2006) were utilized grounding the foundation for other prerequisites in order to perform the assessment.

Having the chosen assessment model in place it called for a need of gathering all the input data required for the assessment. To identify the current practices existing assessment tools were researched and analyzed. It was found that most of the existing or scholar proposed approaches relies on IFC with additional tabular data as an input or BIM proprietary tools to conduct the assessment. Under further study these approaches brought a number of connected issues. It was revealed that storing Circular Economy related data in BIM models is inconvenient for variety of reasons like model redundancy, data reusability or manual input concerns to name a few. Furthermore, when exporting the BIM model as an IFC format it was found that the IFC data model itself lacks the structure to capture CE related data.

Another concern was imposed associated to the ambiguity of where to find and how to retrieve the circularity assessment required data. To answer this question a research on existing databases related to CE were carried out. Unfortunately, the research results showed many issues connected with the existing data structuring, storage and sharing practices. First of all, it was observed that there is no common structure to store the data. This issue made the researchers look back to the concept of Material Passport searching for the propositions for a common structure. However, it was found that current suggestions for MP have a lot of deficiencies as well, most importantly lacking the technical properties like disassembly factors, which are crucial for the technical circularity assessment. Further looking into the possibilities for data structuring most commonly used documentations were reviewed. Environmental Product Declarations or EPDs were found to be one of the most frequently mentioned. Some databases set in different countries like Oekobaudat, Ibu Data or EPD International were based on EPDs to provide information on product properties. However, while querying products between the same structured databases still some data inconsistencies were found and even in the same database some products held more information than others. Furthermore, EPD documentation showed similar issue as the MP proposed structures lacking the technical indicators for circularity assessment.

Several more concerns were found regarding the existing databases where one of the highest importance is the accessibility. A number of databases were found commonly coming together with some kind of assessment system from a proprietary software. It was discovered that vendors tend to collect the data in their own closed environments meaning that it would require a license or in some cases maybe a few in order to reach a high assessment accuracy. Furthermore, the databases are presented in many different formats varying from tabular data in Excel sheets to web-based representations and the extensiveness diverge from a couple of hundreds of products to thousands. Finally, the geographical location of a product also plays a role while choosing the right item. Most of the databases represent country specific products, therefore if the user cannot find a product relatively in reachable distance, they will be forced to choose other alternatives with no circularity data provided.

Most of these problems together with general data management issues in AEC industry like large amounts of heterogenous data scattered across different domains and lack of common data environment was addressed and confirmed during the interviews with industry professionals. Based on this information three user stories were defined, and system requirements drawn towards a novel approach for building circularity assessment at early design stage.

The analysis of Design for Disassembly factors has shown that not all of them can be determined at the early design stage and most of them are subjective to a designers' or manufacturers' opinion. This demonstrates the ambiguity that still lies in the assessment approaches and the necessity for a qualified designer in order to be able to specify the subjective matters. However, some data can be provided based on fixed factors and stored in a database for the assessment. This type of data is suggested to be added to a buildings' Material Passport and in the case of this study was grouped in four categories including (1) general information about manufacturer, (2) general information about the product, (3) product composition and (4) disassembly factors. As it was identified previously among other basic information it is necessary to know the product location and the life-span regarding the assessment. Other crucial information is the material composition and specifically the mass of non-virgin input and reusable output of each material as well as the disassembly factors deemed to be possible to be objectively determined by the manufacturer namely: geometry of product edge, standardization of product edge, type of connections, accessibility to fixings and intermediary and morphology of joints.

Semantic Web and Linked Open Data technologies have demonstrated a great potential to overcome the data management issues and by the use of ontologies provide the necessary structure for storing assessment related information. However, the analysis of the currently existing ontologies revealed the lack of vocabulary definition for circularity assessment data. Therefore, the need of a new or extended vocabulary in order to complete the novel assessment framework became obvious. A concept for a new Building Circularity Assessment Ontology (BCAO) was proposed encompassing the structure to organize and connect product, material and manufacturer data related to circularity assessment.

Having the data structuring and storing matter addressed, a circularity assessment conceptual model was proposed including three main layers namely user layer including designers and manufacturers, application layer including two web-applications dedicated for each side of the stakeholders and data layer representing the circularity assessment knowledge base. A separate application to enter manufacturer data was suggested in order to overcome the before mentioned issue regarding the variety of approaches currently manufacturer data is stored and shared. The main purpose of this application is to convert the data into RDF triples later to be stored in the manufacturer data knowledge base. Regarding the limitations of limited web-storage possibilities and necessity for product data ownership it is advocated to store the data in separate stores, however the main user (in this case being the Architect) should be able to access all the data at once by the use of the assessment application.

The concept of an open web-accessible knowledge base has eliminated the need to store additional data in the BIM model at the same time overcoming the IFC data model issues as in this case only the main data about the model elements like the naming or area/volume is required to be exported as a user input for the assessment. However, before starting the assessment, an additional step is required to convert the IFC model to Linked Building Data (LBD) in order to match the data models. Even though, currently there is an openly available tool for this procedure, it is recognized as a not very user friendly step. Finally, the assessment application itself should contain sufficient functionalities like grouping projects' elements, allowing necessary user inputs and retrieving the data from the knowledge base in order to calculate material, product, system and building circularity indicators.

The concept of system framework has demonstrated that once again the product knowledge base is the core element for the system to function. Therefore, BCAO ontology development was continued as a first prototype. After the analysis of the potentially reusable ontologies, finally was chosen to implement the BCAO ontology in Protégé as a new ontology without reusing or extending the existing ones. This decision has been made based on several factors mostly related to the present development issues of available ontologies and the concerns about the unnecessarily complex taxonomy results. However, the benefits of extending or reusing some existing ontology classes are acknowledged and the possibility for that is seen in the future work.

A new BCAO ontology was defined in *Protégé* based on the user stories and assessment model needs. The new ontology classes were structured according to the types of information was recommended to include to a Material Passport previously namely the *bcao:Manufacturer*, *bcao:Product*, *bcao:Material* and other classes related to disassembly factors. Subsequently, the main disassembly classes were expanded to specific factors in that way creating the class taxonomy. The *Protégé* functionality to create restrictions was found to be very useful in the light of the assessment model as it was possible to create rules for correct data representation. However, regarding the time limitations of the project only the first two steps of LOT methodology for ontology creation were possible to accomplish leaving the BCAO ontology only locally defined and not published for on-line use.

A case study including a simple BIM model representing an early design of a residential house was employed in order to validate the structure of BCAO ontology and make sure all the necessary data for technical circularity assessment can be stored in a proposed structure. The model served for the quantity take-off while providing the model elements with their basic properties like area or volume for the assessment. Even though, during this study a technical implementation of the assessment application was not proposed and IFC export was not needed, it is found convenient that for the proposed framework the capabilities of IFC data model is sufficient while representing the basic element data. As was mentioned previously, currently the manufacturer data is stored and shared in different structures and formats. Therefore, to overcome this issue for ontology validation reasons an *Excel* based spreadsheet containing sample manufacturer data was created and used. This data was mapped according to the new BCAO ontology using *OpenRefine* software and created triples exported in TTL format. The ontology together with the exported triples were loaded to the *Apache Jena Fuseki* triple store and queried using SPARQL query language.

The query results showed that the assessment relevant data could be retrieved back depending on user demand. Meaning that if the user would need to find for instance, all the walls in the database with specific utility factor, location, manufacturer, or any circularity indicator it would be possible to do. Furthermore, by the use of the ontology other connected data can be found. For example, if the user found all the walls with the utility factor of 75 years and wants to see the properties of the materials these walls are made of, they can query further and retrieve that data. This reveals the value of Linked Open Data as it provides not only a convenient way to share and structure the data but as well to infer new information.

However, to retrieve the data is only the first step towards the circularity assessment. Once again as the technical implementation of assessment application was not proposed to make sure that the ontology has sufficient structure for systemizing data for chosen assessment model manual calculations were performed. The calculations showed that the data retrieved by querying the triple store is satisfactory and two building layers namely structure and space circularity indicators MCI, PCI, SCI and BCI were calculated. Furthermore, as the assessment application should not only assess the design but give suggestions for a more circular decisions, supplementary calculations for alternative option were done. The calculations showed that in reflection of the described use case gypsum partition walls were more CE friendly then concrete ones chosen in the initial user design. These results demonstrate the value of assessment while making the design decisions which are especially important at the early design phase.

The creation of the conceptual assessment system framework and the first prototype showcase the potential lying behind the implementation of Linked Open Data technologies for building circularity assessment at the early design. During this research it was revealed that many of currently existing data management, storing and sharing issues can be overcome by the use of LOD. Even though, it is acknowledged that the first prototype still needs many iterations and user input to be able to process the huge amount of data related to circular products it is considered as a valid proof of concept to proceed with further steps in the future.

9. Limitations

A number of limitations related to potential user involvement, time restrictions and lack of researcher's technical knowledge have constrained the further development of this study. Time restrictions had a great impact on the user involvement as only a limited number of interviews were carried out in order to identify the current industry state in relation to circularity assessment at the early design stage and confirm the desk research results. These inputs were used further to derive system requirements, however without the following user feedback only one iteration of prototype development was possible to reach. This as well have affected the validation of the assessment framework concept proposition and it is acknowledged that in order to move forward with system implementation, user reflection is critical.

Furthermore, due to time limitations the assessment model was simplified while involving only the objective Design for Disassembly factors which are possible to be predefined by manufacturer, while leaving six other subjective aspects not included in the model. The included aspects were proposed to be incorporated into future buildings' Material Passport, however in view of the ambiguity still lying beneath the concept the full structure of a MP was not proposed as it is as well not the purpose of the study. Therefore, the new proposed BCAO ontology as well was structured based on before mentioned prerequisites. Additionally, time limitations have defined the extent of how far the ontology can be developed, in this case limiting it to local implementation while leaving two following steps namely on-line publishing and ontology evolution for future work.

Moreover, the assessment framework conceptual model is presented only to showcase the connection between different system layers and possibilities lying behind the concept. By the virtue of limited author's IT knowledge further technical details were not explored. Finally, due to the vast number of issues found related to the manufacturer data structuring, storage and sharing it was not attempted to retrieve real data from existing manufacturers and only for the purpose of ontology validation a collection of mock-up manufacturer data created.

10. Conclusion

This study was aiming to answer the main problem formulation and four following sub-questions stated in the introduction of the report:

How can Linked Open Data technologies be utilized for building's circularity assessment at early design stage to guide design decisions towards circular building?

1. What criteria is necessary to assess and what are the existing assessment practices/models?
2. What are existing practices for structuring and storing material/product information necessary for assessment?
3. How can Linked open Data technologies aid for structuring and storing necessary data for circularity assessment?
4. How the proposed solution will guide design decisions toward circular building?

According to the proposed research design model the first two sub-questions were answered during the desk research. It was found that currently there are many different approaches proposed by scholars on how to evaluate building's circularity. The amount of indicators suggested is overwhelming and therefore, many approaches are recommended for structuring them either by indicator type, phase of life cycle of building when it is assessed, type of field they address, etc. However, as this study was aiming at proposing a technical solution for circularity assessment at early design stage the indicator research was restricted to technical indicators. In the light of that, five most referred assessment models were compared for eight technical input indicators and five technical output indicators. Finally, during the assessment models analysis three scholar works were utilized namely Ellen MacArthur Foundation & Granta Design (2015), Verberne (2016) and Durmisevic Elma (2006). To comply with the selected models and calculate MCI, PCI, SCI and BCI the information needed about building products is the mass of each material non-virgin input and reusable output, total mass, product edge standardization, product edge geometry, morphology of joints, fixing factors and connections.

Continuing with the desk research the current assessment relevant data structuring, storing, and sharing practices were uncovered. It was found that presently there is a vast amount of heterogenous data scattered across different domains and no platform available to access all that data at once. Furthermore, while researching available databases it was revealed that some of the technical indicators necessary for the assessment are present only in a few of the existing platforms and some of them were not found anywhere at all. On top of that many other issues were discovered related to the data accessibility, reusability, reliability, etc.

Linked Open Data technologies were found to be very promising in order to resolve the before mentioned data management issues. By the use of ontologies, the assessment needed data can be structured in the consistent way and made available on the Semantic Web. However, it was revealed that currently there is no ontology present able to provide necessary vocabulary for technical circularity indicators. Therefore, a new BCAO ontology was proposed and tested for accuracy, usability, and assessment needs.

The ontology prototype validation was performed by the means of a use case while exporting the BoM of an early design of residential house BIM model and employing mock-up manufacturer product data structured according to the proposed BCAO ontology. The query results from created triple store database were employed in order to manually perform the assessment calculations according to the selected models. The calculations showed that the query results were sufficient to perform the assessment. An alternative calculation for different products were made in order to compare the first results with the alternative. In reflection to the described case the alternative results came to be more satisfactory. This proves the possibility to use the assessment not only to find out the score for an initial structure but as well to see the other possibilities, therefore paving the way for a better design decision.

Based on the findings of this study a conceptual circularity assessment framework was drawn combined from three layers namely, user layer including designers and manufacturers, application layer including the assessment application and an application to enter the manufacturer data, and data layer representing the knowledge base. This framework illustrates how the assessment application can make use of the LOD knowledge base in order to retrieve information for the circularity assessment.

11. Future Work

The conceptual assessment framework and the first prototype presented in this study, illustrates only the first steps towards the circularity assessment system implementation in practice. Therefore, there is still a lot of work to be done in order to bring this concept to reality. First of all, the manufacturer knowledge base has to be addressed as it was found to be the core for the proposed framework to work. Currently only the first prototype of a new BCAO ontology for structuring the manufacturer data was proposed. In the future this otology should be reviewed, updated, and possibly adjusted while incorporating the definitions from already existing vocabularies. Furthermore, the ontology should be explained and published online, while making sure to follow the ontology evolution recommendations. During all these processes according to the LOT methodology developers, users and domain experts should be involved.

Furthermore, in order to be able to convert manufacturer data into triples it is suggested to develop a common manufacturer web-application, which could be utilized to enter manufacturer data in unambiguous manner. The application should be open to all data providers, however data privacy must be ensured by user authentication systems.

Even though currently there are a few platforms available for circularity assessment it was found that there are some issues with the assessment models utilized by those applications, especially regarding the lack of implementation and accuracy for technical circularity indicators. Therefore, for the selected assessment model to work an assessment application should be developed incorporating all the functionalities like product filtering, visualization, model elements grouping, circularity indicators calculating, and others previously uncovered by this study.

Finally, to make the process more user-friendly it is recommended to eliminate the intermediate step for the user manually exporting the IFC model to Linked Building Data. This could be done by incorporating the LBD convertor to the web-application, where the user would be only required to upload an IFC model and the conversion would be done automatically.

Regarding the delimitations stated in the beginning of the report, only the technical development future work was discussed. However, the authors are well aware about the management, legislation and other implementation barriers affecting the suggested solution. It is as well acknowledged that the creation of the manufacturer knowledge base alone is a complicated and time-consuming process. Nevertheless, the need for it is clear hence even a small step matter.

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Appendix A: Interview summaries

INTERVIEWEE A

Introduction.

Introduce yourself. What is your role at the company? How many years of experience you have? What types of project you are involved in? Could you walk us through your typical project?

She has 16 years of experience in various roles such as consulting, business development and specialist project manager. Her background is in earth science and now she is the executive director of an earth science matters foundation, it is an organization which communicates the matters of the earth to broader audience and it also promotes science based relevant technology solutions. Also, she is a cofounder of the *Transformation* which is the hackathon that will be looking at the energy transition.

Based on her background in earth science, she mainly works on site investigation projects or prepare for large infrastructure projects either on shore or offshore.

1. **Circular economy**

   1.1 What do you know about the circular economy concept?

Interviewee worked for a consulting company, the company worked with a whole building environment as it has engineers and architects. the consultants in the company used to ask the client if they are interested in sustainability, and they try to incorporate sustainability practices with their project. Which includes topics within circular economy. However, she was not familiar with how they are dealing with these aspects in their project.

While working for the consulting company, she was involved in the internal foundation design in hackathon to explore circular community. Based on the exposure she had, she learned that circular economy **means how to get products from raw material or reuse them or repurpose them to minimize the waste in the environment**. In other words, her understanding of the circular economy is to have everything from source to grave and try to get that in a full circle with minimal thing going to the grave. As for the social aspect, everybody is sharing and living off of everybody's things, so nobody owns anything, they are all working together.

2. **Design strategies**

   2.1 Do you use any design strategies (Design for Disassembly, Design for Adaptability, C2C, etc.) /certifications (DGNB, EPD, ISO, LEED, BREEM, etc.) related to sustainability or circular economy in your work? Which ones and what are the reasons?

   In Some of the discussions design for disassembly is the concept that they were thinking of for the circular society that they were proposing for a region in Netherlands. She thinks that the **focus on circular economy is now increasing**.

   Based on the experience she had on hackathon, she started to think on how to incorporate these principles (circular economy) even in the early stages of her work.

For that, she was looking to use underground cities or societies to **minimize waste** so they do not have to rebuild as often but they can implement these in more circular approaches.

Also, she is not sure about the certificates but the **company where trying so hard to get the LEED certificate, they wanted to show that they are environmental**.

2.2 How much material information is available when starting the design process?

The interviewee is not sure about how much information is available. Because her work is after the design is already made. She is not involved in design process.

2.3 Have you heard about the concept of Material Passport? Is it used in your company or by company partners? Do you see any benefits/drawbacks of it?

Not sure about the concept.

2.4 What kind of material data do you have access to? Is it directly from manufacturers or external databases? In what format you can retrieve that data? Do you have access to additional data if you need to?

The interviewee is not connected with the design process and material data in their company. As she starts with early foundation stages of the project to check the site at first, then look on the geological information, the ground soils, what is the environment, the typography, and the geomorphological environment that the infrastructure will be built on. Then she checks the ground if it is load stability, or there will be flooding.

During the construction she checks when they are hammering piles if there will be any impact on the material, she makes sure to tell the engineers if there is a hard material or rocks when they are hammering to change the place of the pile or change the type of pile.

As for her work in the Hackathon, the interviewee is going to help oil and gas companies transition to renewable energy. And how to diversify their portfolio so the challenges to look along the value chain of the oil and gas sector. Also look at the renewable sectors to see where there are interconnections, particularly to look **if there are ways to use or reuse or recycle the materials that have been used**. Because there is so many assets and money that has been spent on it, such as the environment resources that has been used already to buildup pipeline structures that maybe can be reused in a renewable sense for example to use pipelines to transport hydrogen instead of oil and gas.

According to the interviewee point of view the demand on the resources and materials is high and if companies do not implement a strong circular approach to the solutions that they are coming up with its not going to be sustainable. In other words, if they do not find a circular approach to solve their problems resources and materials will not be maintained and they will be solving one problem to create another one.

The point of the hackathon she is working on is to consider the future solutions that are more environmental and to really take the pressure of the demand on the new resources and try to reuse or reapply what already has been used.

2.5 Are you familiar with design for disassembly concept and do you take in consideration the reusability of material at building end of life?

Mentioned as a part of question 2.1, the interviewee is not aware of the concept and have not taken part in any related projects.

3. Data handling

3.1 How do you store and share the material data within the company and partners? Do you see any issues in the current ways? What could be different?

The interviewee has a **limited material data information**. She does not know where they store the data.

3.2 Imagine there would be an open linked database carrying material passports and other circularity assessment related information collected from various stakeholders like designers, manufacturers, governmental institutions, etc. Do you see any benefits or drawbacks this kind of technology might bring? Would you find it useful and how?

According to the interviewee point of view having an open linked data base is a **good thing**, but it has its **limitation**s as it might not work with everyone unless it is entered in **harmonized way**. So, for an open linked data there should be **quality control** to ensure all the data entered. Even for people speaking the same language there is **different terminologies** for different things but they mean the same thing. If information is being entered not harmonized, then the results are not as they should be. By the interviewee experience **dropdown menus** could help a lot in an open database. So, the **users would not be allowed to enter terminologies as they want, and the maintenance team could have a full control on the entered data**.

4. Assessment

4.1 Do you know any assessment frameworks/tools related to sustainability or circular economy applied to the preliminary design? Do you use any of those in your work? What encourages/prevents you from using them?

As the interviewee is only working with early foundation stages and soil solutions. She is not involved in this type of assessment.

INTERVIEWEE B

Introduction.

Introduce yourself. What is your role at the company? How many years of experience you have?

The interviewee is currently the head of digital innovation at a large construction consultancy company in Denmark. He has done a PhD and have been working in the industry for more than 15 years.

1. **Circular economy**

   1.1 What do you know about the circular economy concept?

   The interviewee has a **good understanding** on Circular Economy. He argues that most people when they think about Circular Economy, they speak about the **cost** part, but it should be seen in **a broader perspective**.

2. **Design strategies**

   2.1 Do you use any design strategies (Design for Disassembly, Design for Adaptability, C2C, etc.) /certifications (DGNB, EPD, ISO, LEED, BREEM, etc.) related to sustainability or circular economy in your work? Which ones and what are the reasons?

   The interviewee introduced **EPDs** as a way to define manufacturer data. However, he pointed out that even though the standard is requiring to define the same information, **the outputs still vary a lot** regarding **the data provided, the structure of that data and in what format it is presented**. For example, he indicates that he has seen different types of EPDs where in one declaration information is put on the top while in the other the same information can be found in the bottom of the document. As well as the files were represented in different formats like **Excel files or PDFs**. According to him is not possible to make an automated collection of this data, therefore you need to **type it in manually from all the different sources available**. Furthermore, he continues saying that the data provided by EPDs in **not extensive enough** as it could be enriched with the information about maintenance, life span, etc.

   As well he is well acquainted with other certifications like **LEED or DGNB**, interviewee indicates **DGNB as the most widely used in Denmark**. He sees **a high rise of demand** for these kind of documentation for projects in the industry. For example, a couple of years ago these kinds of certifications were not very widely referred, however now according to the interviewee they are commonly discussed for the biggest part of the projects. The reason for that, he exposes the **market requirements**.

   When asked about any design strategies like **DfD**, the interviewee said that to his knowledge they are **not implemented** in the work practice at the moment. However, there were some **discussions** about that.

2.2 How much material information is available when starting the design process?

The interviewee sees a **big challenge in connection to the knowledge about materials for the early stage of design.** He points out the **need for that information**.

2.3 Have you heard about the concept of Material Passport? Is it used in your company or by company partners? Do you see any benefits/drawbacks of it?

The interviewee is **aware of a concept of MP** and agrees that so far it **is missing a clear widely used structure**. As well he gave an example of Material Passport currently being developed by Danish organization Molio with Norwegian company named CoBuilder which is also in collaboration with ISO standardization. However, he points out that this is a commercial company which aims to help companies to define the standards for internal processes related to sustainability.

Furthermore, he specifies that it is important when creating a MP to look at the **common understanding**, rather than own perspective as otherwise it might become **useless in the long run**.

2.4 What kind of material data do you have access to? Is it directly from manufacturers or external databases? In what format you can retrieve that data? Do you have access to additional data if you need to?

The interviewee had mentioned before that there are currently many ways where information can be found, however it **is scattered between various domains and formats**.

2.5 Are you familiar with design for disassembly concept and do you take in consideration the reusability of material at building end of life?

The interviewee is familiar with the concept, however **not implementing** it in a workplace.

3. **Data handling**

3.1 How do you store and share the material data within the company and partners? Do you see any issues in the current ways? What could be different?

In their design work they deliver a lot of information for the client **in various formats like IFC, REVIT models and written documentation in Excel, Word or PDF formats,** etc. However, it is based on their **internal data handling structures as there are no common standard**.

3.2 Imagine there would be an open linked database carrying material passports and other circularity assessment related information collected from various stakeholders like designers, manufacturers, governmental institutions, etc. Do you see any benefits or drawbacks this kind of technology might bring? Would you find it useful and how?

The interviewee indicated that the idea to have a **connection between BIM model and a rich material data source has been there for years**. He was involved in some projects have trying several methods to achieve this goal by **connecting some external data sources or entering the data directly** to the model as a property, but unfortunately **none of the approaches were successful**. The interviewee suggests that the reason for that is a **lack of standard** to structure that data and base it on. He points out that it is a **huge effort to collect the material data** because it is so **unstructured.**

In relation to the **significant life span of the buildings** the interviewee thinks that it is obvious that relevant **information should be stored in an open, machine readable format which is not fixed to a specific software.**

4. Assessment

4.1 Do you know any assessment frameworks/tools related to sustainability or circular economy applied to the preliminary design? Do you use any of those in your work? What encourages/prevents you from using them?

The interviewee himself is not working with any assessment models or tools, and to the extent of his knowledge it is also **not done in the company he is currently working** in. However, he indicates that this topic **is discussed in the work environment** in order to establish a practice. The main barrier for that he sees the **lack of initiative from the owner**, as the main clients of the company are private developers who **aims at the lowest costs and fastest establishment.**

As well he indicated that in Denmark there are some regulations pushing the companies to implement Life Cycle Assessment for example. He indicated that in a couple of years those regulations should come into practice insisting the builders to provide LCA documentation of the project in order to get building permit.

INTERVIEWEE C

Introduction.

Introduce yourself. What is your role at the company? How many years of experience you have?

The interviewee is a managing director (who is also a civil engineer) of a large international company providing a wide range of assembly details for concrete structures and composite beams located in Denmark. He has experience in the company for almost 15 years.

1. Circular economy

1.1 What do you know about the circular economy concept?

The interviewee is **well aware about Circular Economy** and his company has been **involved in some initiatives** regarding the concept. As well Circular Economy is one of the three points included in the companies' strategy. Currently there are three projects going on in Denmark, Norway and Finland where the company is participating. From the experience working with the circular house project in Denmark, the interviewee pointed out some challenges while taking this approach. One of them was the **difficulties to secure the stability**. According to him there is also a **gap in the education and specialization of current engineers** as additional knowledge is required while designing from reused elements. For example, compression is the hardest point to address, while the tension could be taken by the use of steel.

2. Design strategies

2.1 Do you use any design strategies (Design for Disassembly, Design for Adaptability, C2C, etc.) /certifications (DGNB, EPD, ISO, LEED, BREEM, etc.) related to sustainability or circular economy in your work? Which ones and what are the reasons?

As the company specializes in assembly parts it **is fully cognizant about Design for Disassembly**. According to the interviewee initially the organization was not intended for the matter, but now **environmental problems push the industry** to recognize the potential and benefits of the approach.

EPDs are used as well. All the products provided by the company comes with a EPD which are **published on the website.** However, it was pointed out that **EPDs differ for the same product I different countries** due to **differences in the manufacturing processes and country specific regulations** for CO2 emissions.

When asked about the design of their products the interviewee indicated that the **goal is to optimize the usage of the of material** by providing better assembly solutions. For example, the thickness of the wall can be reduced if the connection parts take less space at the same time fulfilling the functional requirements.

3. Data handling

3.1 How do you store and share the material data within the company and partners? Do you see any issues in the current ways? What could be different?

For internal component data storage company uses **ProdLib software** which also provides the connection with the CAD software. However, the interviewee recognizes that this kind of approach lead to a **closed environment and the data is not easily accessible for other stakeholders.**

3.2 Imagine there would be an open linked database carrying material passports and other circularity assessment related information collected from various stakeholders like designers, manufacturers, governmental institutions, etc. Do you see any benefits or drawbacks this kind of technology might bring? Would you find it useful and how?

The interviewee agrees that this kind of solution **would speed up the Circular Economy implementation** process. However, have showed some **considerations about sensitive data privacy** and expressed the need for a **standardization** as well as **legislations** to implement the solution widely.

INTERVIEWEE D

Introduction.

Introduce yourself. What is your role at the company? How many years of experience you have? What types of project you are involved in? Could you walk us through your typical project?

Have been an architect for 10 years. For the last 7 years worked in an architecture company which not long ago was joined with a large international engineering and architecture consultancy company. His role at the company now is project architect and project manager. The exact role depends on the project. Works on many different projects like housing, high rise buildings, schools, stadiums, etc. Works as well with sustainability and DGNB. Took the course to qualify as DGNB consultant, as well different LCA and LCC courses. Worked with that as well on several projects. Currently is not involved in any sustainability or CE related projects but tries to integrate the concepts to the projects he is running.

5. **Circular economy**

1.1 What do you know about the circular economy concept?

Knows a lot about the concept itself. Unfortunately, recognizes that it is **not much integrated to the work environment**. Some companies have more focus on it than others, but the **demand normally comes from owners and currently he is not seeing much of it**. Interviewee says that **the CE regulations are coming to DGNB certification** as a part of it. He personally tries to choose the materials with circularity in mind for projects, but he says that it is **driven by project manager** and his knowledge as well as ambition in that regard.

6. **Design strategies**

2.1 Do you use any design strategies (Design for Disassembly, Design for Adaptability, C2C, etc.) /certifications (DGNB, EPD, ISO, LEED, BREEM, etc.) related to sustainability or Circular Economy in your work? Which ones and what are the reasons?

Regarding **Design for Disassembly** according to the interviewees point of view it **is driven by architect himself**. As he is a sustainability expert, he often tries to integrate wooden constructions for example, but at the same time meets a lot of **barriers from different parties like colleagues and engineering part especially**. Even thought, he had succeeded to implement some DfD friendly elements into the project, still has not done any full DfD compliant project yet. However, he sees that **this is the way industry is going** and forecasts that it could be pushed with some **legislations**.

Regarding the **DGNB** certification the interviewee sees **some issues in the whole certification system** as it brings very **minimal actual change** in projects and **works more for the sails process**. The builders tend to **chase for certification** points that cost the less which shows a good score but do not really make the building much more sustainable.

2.2 How much material information is available when starting the design process?

Normally finds material information **on manufacturer websites**. For sustainability or carbon emission data are using LCAbyg software, but mostly only when they need to make certifications. However, **admits that would be good if there would be a place to look up materials**. Have **discussed within the company** to make some **material catalogue internally**, both presented with visualization and related data. Says that **not all project architects are familiar with the data and are more visual minded**.

2.3 Have you heard about the concept of Material Passport? Is it used in your company or by company partners? Do you see any benefits/drawbacks of it?

The interviewee is **aware of Material Passports**. The company **do not have internal structure** for it, but when choosing materials mostly relies on **costs and maintenance factors**. **CO2 emissions** comes as a third indicator, without taking **aesthetics and function** into account. After these indicators comes into consideration the **amount of reused or recycled materials embedded in the products and if they can be reused or recycled at the end of buildings' life**. The interviewee argues that these factors comes into consideration first as they are **easy understandable for the client**.

2.4 What kind of material data do you have access to? Is it directly from manufacturers or external databases? In what format you can retrieve that data? Do you have access to additional data if you need to?

The information is available, he did not experience a situation where he needed some information, and it was not accessible. However, interviewee *had* some **issues with the quality of information**. For example, he noticed a **big difference in the data provided in manufacturer website compared to data in LCAbyg**. This issue brought out an ambiguous position which one to use.

2.5 Are you familiar with design for disassembly concept and do you take in consideration the reusability of material at building end of life?

This question was answered partly answered in question 2.1. When asked more in depth about consideration of **disassembly factors** for example, the interviewee said that this is a question more relevant for the people who works with a **detailed design**. However, **some junctions between elements are given from the beginning** of the project as part of the element and they do not need to redesign them. Requirements for the disassembly factors **never came from the owner** in interviewees experience.

7. Data handling

3.1 How do you store and share the material data within the company and partners? Do you see any issues in the current ways? What could be different?

When they do certifications and LCA they have a **digital archive where they put the EPDs and assessment results**. The archive is file folder based and EPDs are stored in **PDF** file format. **One of the problems he sees in this type of storage is updating as EPDs has limited time to be valid.** Furthermore, when asked if it takes a lot of time to find necessary information, the interviewee said no, because he **would not search the EPD data there, but rather go directly to manufacturers' website.**

Also, some catalogues are saved as templates for LCAbyg. LCAbyg as well is used for accessing some **external databases like Oekobaudat or Sustainability sheets from Green Council**. However, interview indicted that **rarely all the necessary information is present in LCAbyg**. Therefore, normally they have to go in and **build the information themselves** using data from Oekobaudat or EPDs. Nevertheless, there is **big risk of failure** by doing that mainly because of **typing mistakes and unit translations, which leads to miscalculations** for the whole building. Therefore, the interviewee **does not find it really reliable**.

Some information is as well **stored in the BIM models** in individual projects. There has been talks in the company about **linking Oekobaudat database directly to BIM model**, but it is still just one of the ideas that was not pursued. When asked if the additional data makes the model more redundant the interviewee disagreed and said that **mostly only the visual parts slows the model down**. The data embedded in the model later **is exported as an Excel format** and used for Life Cycle Assessments. However, when the data is put out it becomes a **"dead" spreadsheet** and if they have to pull it out again from the model, they have to go through it once more to **check all the naming, structure and sorting**. The pulled Excel files are used only for certifications and used **only for that one project**. To reduce the manual input in the BIM model the company has some **internal product templates and assemblies** for Revit to load, but it is not possible to have it all due to the **big variance of projects**. Still, it was stressed that there **should be a concrete guideline** to pull out the data correctly. As well it was indicated that models are **missing the necessary level of detail and brings some issues in the way they are built**.

Also, as he said before there have been discussions in the company a couple of years ago about **internal database structure**, but it was not perceived. Working in a big company interviewee sees as a drawback in this case as the **database has to be extensive and universal for the whole organization**. Still, they are moving towards that direction by **making digital tools and programming their own software for different cases**. When asked about the information sharing the interviewee says that **if there would be some initiative for a shared platform they would probably join, but they would not initiate it themselves**.

3.2 Imagine there would be an open linked database carrying material passports and other circularity assessment related information collected from various stakeholders like designers, manufacturers, governmental institutions, etc. Do you see any benefits or drawbacks this kind of technology might bring? Would you find it useful and how?

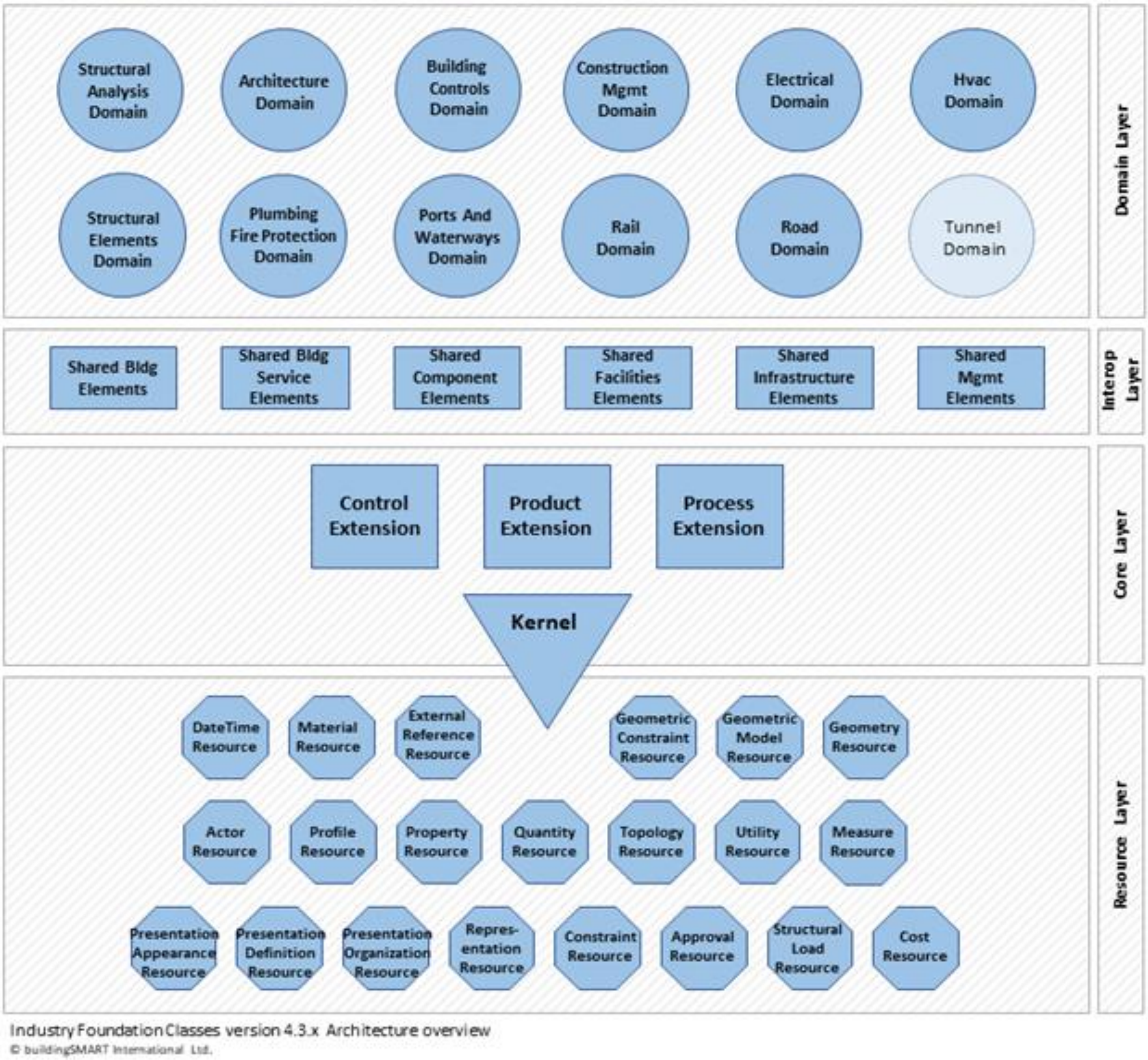
The interviewee sees this type of database **useful,** further indicating the **gaps in the current information provided on circularity assessment**. As well makes a point related to the **significant life span of buildings** and the **necessity to carry that data in a platform that is time resilient**. In his opinion this information might be even of a **greater value in future** when new technologies that are presently researched (for product recycling for instance) will be developed.

8. Assessment

4.1 Do you know any assessment frameworks/tools related to sustainability or circular economy applied to the preliminary design? Do you use any of those in your work? What encourages/prevents you from using them?

As he mentioned before they use **LCAbyg**. They have tried **One Click LCA**, but they are not using it anymore. Interviewee mentioned the **material pyramid** as well which is recently made by architects in Copenhagen for a fast material assessment in terms of **CO_2 and other LCA criteria**. However, the user has to be aware of **mass calculations and not all materials are included**. So, all in all they are using only the LCAbyg at the moment and the information available on external sources. As the main drawbacks in the presently used tools the interviewee sees the **reliability of the data, manual input and large geographical distribution.**

Appendix B: Overview of IFC 4.3 RC2



Appendix (B) General overview of the IFC 4.3 RC2 conceptual organization adopted from (BSI, n.d.)

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Appendix C: Bill of Materials

Wall Schedule									
Area	Family	Volume	Width	Unconnected Height	Type	Structural Material	Length	Function	Count
8.34 m²	Basic Wall	2.92 m³	350	2530	Sandwich (concrete-brick) - 350mm	BIPS_CONCRETE_PRECAST	170,9631944	Exterior	1
30.82 m²	Basic Wall	10.79 m³	350	2530	Concrete - 350mm	BIPS_CONCRETE_PRECAST	12181.41	Exterior	1
20.61 m²	Basic Wall	7.21 m³	350	2530	Sandwich (concrete-brick) - 350mm	BIPS_CONCRETE_PRECAST	396,2965278	Exterior	1
23.82 m²	Basic Wall	8.34 m³	350	2530	Concrete - 350mm	BIPS_CONCRETE_PRECAST	10051.04	Exterior	1
8.79 m²	Basic Wall	3.08 m³	350	2530	Sandwich (concrete-brick) - 350mm	BIPS_CONCRETE_PRECAST	5408	Exterior	1
4.5 m²	Basic Wall	1.58 m³	350	2530	Sandwich (concrete-brick) - 350mm	BIPS_CONCRETE_PRECAST	88,775	Exterior	1
12.11 m²	Basic Wall	1.45 m³	120	2530	Int - 120mm Concrete	BIPS_CONCRETE_PRECAST	5614.87	Interior	1
17.9 m²	Basic Wall	1.79 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	396,2965278	Interior	1
12.11 m²	Basic Wall	1.21 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	5614.87	Interior	1
5.82 m²	Basic Wall	0.58 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	105,25625	Interior	1
4.91 m²	Basic Wall	0.49 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	2692.86	Interior	1
2.44 m²	Basic Wall	0.24 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	1728.89	Interior	1
8.49 m²	Basic Wall	1.02 m³	120	2530	Int - 120mm Concrete	BIPS_CONCRETE_PRECAST	147,0465278	Interior	1
9.5 m²	Basic Wall	0.95 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	3989.69	Interior	1
8.23 m²	Basic Wall	0.82 m³	100	2530	Int - 100mm Concrete	BIPS_CONCRETE_PRECAST	147,0465278	Interior	1

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Doors & Windows Schedule						
Area	**Family**	**Width**	**Type**	**Structural Material**	**Function**	**Count**
1.73 m²	Basic Door	350	Ext. Single-Flush in: 810 x 2030	Default Door-Window Frame/Mullion	Exterior	1
1.89 m²	Basic Door	350	Ext. Single-Flush in: 912x2145	Default Door-Window Frame/Mullion	Exterior	1
1.44 m²	Basic Door	350	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.44 m²	Basic Door	350	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.44 m²	Basic Door	350	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.44 m²	Basic Door	350	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.44 m²	Basic Door	120	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.44 m²	Basic Door	100	Int.Single-Flush: 810 x 2030	Default Door-Window Frame/Mullion	Interior	1
1.3 m²	Basic Window	100	Fixed: 950 x1212 mm	Glass		1
1.3 m²	Basic Window	100	Fixed: 950 x1212 mm	Glass		1
1.3 m²	Basic Window	100	Fixed: 950 x1212 mm	Glass		1
1.3 m²	Basic Window	100	Fixed: 1212x1212 mm	Glass		1
1.3 m²	Basic Window	120	Fixed: 1212x1212 mm	Glass		1
1.3 m²	Basic Window	100	Fixed: 2090 x 1400	Glass		1

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Appendix D: Manufacturer data

Company name	Company Type	Company Location	Product ID	Product name	Product Location	Utility (years)	Has material	Has material	Has material	Material ID	Material name	(kg/m3)/(kg/m2)/(kg)	Total mass (kg)	Non-virgin input (%)	Reusable output (%)
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1001	Wall 350mm	Denmark	75	C101	S101					2500	52%	100%
										C101	ConcreteC40	2500	2000	50%	100%
										S101	SteelS355JR	85	500	100%	100%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1002	Wall 350mm	Denmark	75	C102	S102					3500	40%	0%
										C102	ConcreteC35	2500	2750	40%	0%
										S102	SteelS355JR	85	750	30%	0%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1003	Wall 350mm	Denmark	75	C103	S103					2500	0%	48%
										C103	ConcreteC40	2500	2000	0%	50%
										S103	SteelS255JR	85	500	0%	0%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1004	Wall 350mm	Denmark	100	C104	S104					2500	0%	0%
										C104	ConcreteC35	2500	2000	0%	0%
										S104	SteelS355JR	85	500	0%	0%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1005	Wall 350mm	Denmark	100	C105	S105					3500	10%	50%
										C105	ConcreteC40	2500	2750	10%	50%
										S105	SteelS355JR	85	750	0%	50%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1006	SandwichWall 350mm	Denmark	75	C106	S106	B101				4500	65%	90%
										C106	ConcreteC40	2500	2750	50%	90%
										S106	SteelS355JR	85	750	100%	100%
										B101	Brick 240x70x112	1000	1000	100%	100%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1007	SandwichWall 350mm	Denmark	100	C107	S107	B102				4500	0%	28%
										C107	ConcreteC40	2500	2750	0%	0%
										S107	SteelS355JR	85	750	0%	0%
										B102	Brick 240x70x112	1000	1000	0%	100%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1007	SandwichWall 350mm	Denmark	100	C108	C109	B103				4500	65%	30%
										C108	ConcreteC40	2500	2750	50%	0%
										S108	SteelS355JR	85	750	80%	100%
										B103	Brick 240x70x112	1000	1000	100%	100%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	IW1001	Internal Concrete Wall	Denmark	20	C109	S109					900	80%	49%
										C109	ConcreteC25	2500	750	80%	50%
										S109	Steel255	70	150	80%	0%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	IW1002	Internal Concrete Wall	Denmark	15	C110	S110					800	0%	0%
										C110	ConcreteC25	2500	600	0%	0%
										S110	Steel255	70	200	0%	0%
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	IW1003	Internal Concrete Wall	Denmark	20	C111	S111					750	40%	50%
										C111	ConcreteC25	2500	550	40%	50%
										S111	Steel255	70	200	40%	50%
Manufacturer2	Gypsum walls manufacturer	Denmark	IW1004	Internal Gypsum Wall	Denmark	15	G101	M101					250	100%	80%
										G101	Gypsum	9.2	200	100%	80%
										M101	Metal	50	50	100%	80%
Manufacturer2	Gypsum walls manufacturer	Denmark	IW1005	Internal Gypsum Wall	Denmark	20	G102	M102					250	53%	31%
										G102	Gypsum	9.2	175	80%	40%
										M102	Metal	75	75	50%	30%

Company name	Company Type	Company Location	Product ID	Product name	Edge standardisation	Edge geometry	Morphology of joints	Fixing factors	Connection
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1001	Wall 350mm	Pre-made	Symetrical overlapping	Knot	Accessible with causing repairable damage	Direct integral
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1002	Wall 350mm	Made on site	With insert on two sides	Knot	Accessible with causing no damage	Direct chemical
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1003	Wall 350mm	Made on site	With insert on two sides	Linear	Accessible	Accessory external
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1004	Wall 350mm	Made on site	Unsymetrical overlapping	Linear	Accessible with causing damage	Accessory internal
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1005	Wall 350mm	Half standardised	With insert on two sides	Knot	Accessible with causing no damage	Accessory internal
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1006	SandwichWall 350mm	Pre-made	Symetrical overlapping	Knot	Accessible with causing no damage	Direct integral
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1007	SandwichWall 350mm	Made on site	With insert on one side	Point	Not accessible	Direct integral
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	LB1007	SandwichWall 350mm	Half standardised	Unsymetrical overlapping	Knot	Accessible with causing no damage	Filled with hard chemical
Manufacturer1	**Pre-cast reinforced concrete elemets manufacturer**	**Denmark**	**IW1001**	**Internal Concrete Wall**	**Made on site**	**With insert on one side**	**Linear**	**Accessible with causing repairable damage**	**Direct integral**
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	IW1002	Internal Concrete Wall	Made on site	Open linear	Knot	Accessible with causing damage	Direct chemical
Manufacturer1	Pre-cast reinforced concrete elemets manufacturer	Denmark	IW1003	Internal Concrete Wall	Made on site	Unsymetrical overlapping	Point	Not accessible	Filled with soft chemical
Manufacturer2	**Gypsum walls manufacturer**	**Denmark**	**IW1004**	**Internal Gypsum Wall**	**Pre-made**	**Symetrical overlapping**	**Knot**	**Accessible with causing no damage**	**Filled with soft chemical**
Manufacturer2	Gypsum walls manufacturer	Denmark	IW1005	Internal Gypsum Wall	Pre-made	With insert on two sides	Service	Accessible with causing no damage	Direct chemical

Manufacturer3	Door and Windows manufacturer	Denmark	D1001	External Door 810x2030	Denmark	15	W101	MF101		W101 MF101	Wood Metal	40 10	50 40 10	82% 90% 50%	86% 100% 30%
Manufacturer3	Door and Windows manufacturer	Denmark	D1002	External Door 810x2030	Denmark	20	W102	MF102		W102 MF102	Wood Metal	50 10	60 50 10	83% 90% 50%	88% 100% 30%
Manufacturer3	Door and Windows manufacturer	Denmark	D1003	External Door 810x2030	Denmark	20	W103	WF104		W103 MF104	Wood Wood	60 15	60 45 15	100% 100% 100%	100% 100% 100%
Manufacturer3	Door and Windows manufacturer	Denmark	D1004	Internal Door 810x2030	Denmark	15	W105	MF103		W105 MF103	Wood Metal	60 10	35 25 10	9% 0% 60%	73% 80% 30%
Manufacturer3	Door and Windows manufacturer	Denmark	D1005	Internal Door 810x2030	Denmark	20	W106	MF104		W106 MF104	Wood Metal	60 10	30 20 10	59% 60% 50%	90% 100% 30%
Manufacturer3	Door and Windows manufacturer	Denmark	D1006	Internal Door 810x2030	Denmark	20	W107	WF108		W107 MF108	Wood Wood	60 15	35 20 15	94% 100% 70%	54% 60% 30%
Manufacturer3	**Door and Windows manufacturer**	**Denmark**	**W101**	**Window 950x1212**	**Denmark**	**20**	**GL101**	**A101**		**GL101 A101**	**Glass Aluminium**	**35 10**	**35 25 10**	**100% 100% 100%**	**73% 80% 50%**
Manufacturer3	Door and Windows manufacturer	Denmark	W102	Window 950x1212	Denmark	20	GL102	A102		GL102 A102	Glass Aluminium	35 10	30 20 10	53% 60% 30%	61% 70% 30%
Manufacturer3	Door and Windows manufacturer	Denmark	W103	Window 950x1212	Denmark	25	GL103	WW101		GL103 WW101	Glass Wood	30 15	35 20 15	0% 0% 0%	0% 0% 0%
Manufacturer3	Door and Windows manufacturer	Denmark	W104	Window 1212x1212	Denmark	25	GL104	WW102		GL104 WW102	Glass Wood	35 10	35 25 10	0% 0% 0%	0% 0% 0%
Manufacturer3	Door and Windows manufacturer	Denmark	W105	Window 1212x1212	Denmark	20	GL105	WW103		GL105 WW103	Glass Wood	35 10	30 20 10	22% 20% 30%	56% 60% 40%

Manufacturer3	Door and Windows manufacturer	Denmark	D1001	External Door 810x2030	Pre-made	Overlapping on one side	Point	Accessible	Direct integral
Manufacturer3	Door and Windows manufacturer	Denmark	D1002	External Door 810x2030	Pre-made	Symetrical overlapping	Service	Not accessible	Accessory external
Manufacturer3	Door and Windows manufacturer	Denmark	D1003	External Door 810x2030	Pre-made	Symetrical overlapping	Point	Accessible with causing no damage	Direct integral with additional fixing devices
Manufacturer3	Door and Windows manufacturer	Denmark	D1004	Internal Door 810x2030	Pre-made	Symetrical overlapping	Linear	Accessible with causing repairable damage	Filled with hard chemical
Manufacturer3	Door and Windows manufacturer	Denmark	D1005	Internal Door 810x2030	Pre-made	Open linear	Knot	Accessible with causing damage	Accessory external
Manufacturer3	Door and Windows manufacturer	Denmark	D1006	Internal Door 810x2030	Pre-made	With insert on one side	Point	Accessible	Direct integral
Manufacturer3	**Door and Windows manufacturer**	**Denmark**	**W101**	**Window 950x1212**	**Pre-made**	**Overlapping on one side**	**Point**	**Accessible with causing no damage**	**Direct integral with additional fixing devices**
Manufacturer3	Door and Windows manufacturer	Denmark	W102	Window 950x1212	Pre-made	Unsymetrical overlapping	Linear	Accessible	Direct integral with iserts
Manufacturer3	Door and Windows manufacturer	Denmark	W103	Window 950x1212	Pre-made	Open linear	Point	Accessible with causing no damage	Direct integral
Manufacturer3	Door and Windows manufacturer	Denmark	W104	Window 1212x1212	Pre-made	Open linear	Service	Accessible with causing damage	Direct chemical
Manufacturer3	Door and Windows manufacturer	Denmark	W105	Window 1212x1212	Pre-made	With insert on one side	Point	Not accessible	Direct integral with iserts