FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialization: Engineering Structures and Materials / Civil Engineering Structures	Spring semester, 2021 Open / ~~Confidential~~
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Title of master's thesis: Adaptation of circular economy concept into building design process	
Credits: 30	
Keywords: Circular economy Circular design Building Information Modeling Design Passport Construction industry Analytical hierarchy process	Number of pages: 85 + supplemental material/other: ………… Stavanger, 15/06/2021 date/year

Title page for master's thesis

Faculty of Science and Technology

ABSTRACT

Circular economy (CE) is an economic system that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value always, distinguishing between technical and biological cycles. By using circular economy, the value of products and materials is maintained in the economy for as long as possible, thus minimizing the production of waste and reducing/avoiding the extraction of new resources. The main objectives of circular economy in the construction industry are to avoid waste at the design stage, minimize waste generation during construction, preserve the quality and value of materials during operation, and to ensure reusing or recycling of building components and material at the end of the lifespan.

This research investigated the adoption of circular economy in the building design process by identifying and describing the concept, indicators, characteristics, and strategies of circular economy in the construction industry. This study also analyzed the implementation of circular economy in the construction industry by developing a BIM case study to show the adoption of circular economy in the building design process. The case study is a junior high school building in Bogafjell, Norway. The school has a capacity of 504 students, a net area of 9.35m^2 per student. The building is a four-floor structure made of concrete and steel, additionally the school has a pedestrian bridge made of steel and retaining walls on the sides made of reinforced concrete. The BIM model of the case study was provided by the Norwegian consulting company Multiconsult.

This study created a framework of adapting CE in the building design process. A material passport (MP) analyzes the recyclability of the materials in a building once the building is designed and completed. This study proposes a new material passport from the design phase point of view, which will be called Design Passport (DP). The Design Passport will help the structural engineers decide what materials and structural components are better to design a circular building by adopting CE indicators. In the early stage of the circular economy framework, a feasibility study must be included to help construction companies have a better selection of their materials and better product development process for the adoption of circular economy. The analytical hierarchy process assists the construction companies in the decision process of evaluating and determining if a structural element of the project can be reused or recycled. This study selected a precast reinforced concrete wall from the case study to apply the model. A re-evaluation analysis of the structural components is necessary at the end of a project’s life cycle to determine if the components are still in optimal conditions for further reuse in another projects.

The projects in the construction industry vary vastly in sizes, location, materials, and construction methods. This study used a junior high school building as a case study, but the design passport and feasibility study can be utilized in other different projects. This highlights the importance of carrying out case studies to have a better understanding how to adopt circular economy in different kinds of projects. Circular buildings are a relatively new concept construction companies want to implement. Few case studies have been done in the adoption of circular economy in the construction industry.

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ACKNOWLEDGEMENTS

I want to thank God for giving me the opportunity to study in such a great university and country as well as the determination and knowledge to finish my studies despite being away from home and struggling with the coronavirus pandemic.

Secondly, express my gratitude to my supervisors, Samindi Samarakoon and Chandima Ratnayake, for all the guidance, comments, and teachings throughout the two years of my master's degree, especially the fourth and final semester writing the master's thesis.

At last, I would like to thank my friends here in Stavanger as well as my family and my friends back in Honduras for all the support, love and encouragement throughout these two years and my whole life.

1. INTRODUCTION

The construction industry plays an important role in meeting the needs of today's society by improving the quality of life. This sector accounts for 35% of global CO2 emissions and generates between 45 and 65% of the waste deposited in landfills. The construction sector and its associated activities produce a significant amount of harmful emissions, namely, about 30% of greenhouse gases on the planet due to operations during the construction process, 18% of these emissions are caused by transporting and processing construction materials (Alencar et al., 2020).

Buildings are responsible for about 50% of all materials that are extracted from earth. The use of resources for building construction in terms of mass represents one of the biggest challenges in resource consumption. In relation to popular construction materials, concrete used in buildings account for about 75% of total consumption, the use of aggregate materials accounts for about 65%, and the use of steel and wood in buildings account for approximately 21% and 37.5%, respectively (Gervasio and Dimova, 2018). The negative impacts caused by the construction industry are undeniable, highlighting the need to move towards a more ecofriendly or sustainable industry.

Alencar et al. (2020) state that sustainability in the construction industry can help by conserving energy, water, and natural resources through reuse, recycling, innovative design, and minimizing waste and pollution. To do so, proactive measures are taken to reverse or minimize the negative impacts that construction activities have on the environment. Sustainable development enhances the quality of life and consequently allows people to live in a healthy environment and improve social, economic, and environmental conditions for present and future generations (Ortiz et al., 2009).

The study by Alencar et al. (2020) highlights the relevance of sustainability in the construction sector since organizations are increasingly aware that guaranteeing a competitive advantage depends not only on achieving customer satisfaction based on low costs or the quality of the product or service offered. Customers expect companies to respect the environment, be ethical and demonstrate that they are socially responsible.

As mentioned by several studies, there is a high need to achieve sustainability in the construction industry. According to Fořt and Černý (2020) the transition to a more efficient circular model of economics has ambitions to solve the sustainability problems on a higher level thanks to improved recycling and the creation of material loops. This circular economic model is known as circular economy. The following section provides the theoretical background of circular economy and its application in the construction industry.

1.1 Research Motivation

Considering all the environmental impacts generated by the construction industry, the implementation of circular economy is necessary to achieve sustainability. Many studies review the existing literature of circular economy and its components, seldom developing a case study to apply these concepts. The studies that have developed a case study, often analyze how much of the materials from buildings are reusable and recyclable at the end of its life cycle. The application of the circular economy strategies in the design phase of the life cycle of a building results in a higher possibility of having a positive influence. During the design phase, the stakeholders of the project have a greater influence on selecting the construction techniques and materials.

Additionally, developing a case study with a real building model developed by the consulting company Multiconsult will provide a better understanding and validation to the construction industry on how to apply circular economy strategies in the building design process. The case study helps to understand the implementation barriers and benefits that one can expect from circular economy in the future.

1.2 Research Objectives

The main objectives of this thesis are the following:

1. Identify and describe the concept, indicators, characteristics, and strategies of circular economy.
2. Analyze the implementation of circular economy in the construction industry.
3. Develop a BIM case study to show the implementation of circular economy strategies in the building design process.
4. Create an analytical decision hierarchy model to help construction companies in the decision process of evaluating circular economy.

1.3 Research Process

This study consists of a literature review of journal papers and case studies relevant to circular economy in the construction industry. The next step of this research is analyzing the circular economy strategies and apply one of the strategies into a BIM case study. The results of the BIM case study are discussed analyzed. Finally, conclusions and suggestions for further research and improvement are presented. The research process is shown in Figure 1 and consists as follows:

Step 1: establish the objectives for the thesis.

Step 2: literature review to gather the necessary theoretical background for the adaptation of circular economy in the construction industry.

Step 3: identify, describe, and analyze the circular economy strategies.

Step 4: develop a case study to implement the circular economy strategies into a BIM model of a building provided by a construction company.

Step 5: discussion and analysis of the case study

Step 6: write the conclusions for the thesis and suggest recommendations for future research on the subject.

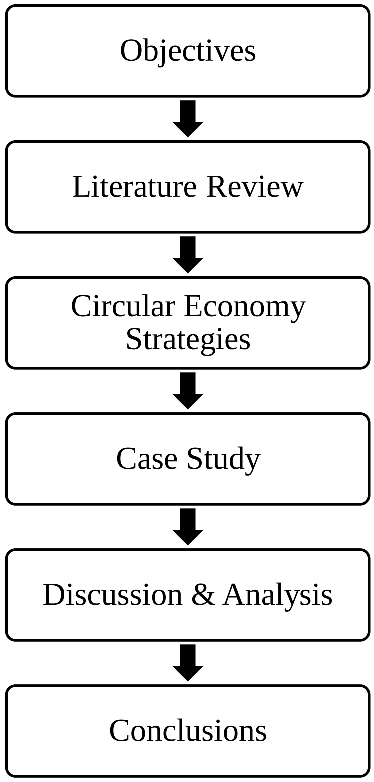

Figure 1 Research process

1.4 Research Scope and Limitations

The scope of this thesis covers the review of twenty published papers from environmental management related journals, to comprehend and analyze all the knowledge and ideas available in the last years, about EMS implementation in the manufacturing and construction industries. Literature review was used as the methodology for this thesis due to the short time frame of this study to develop a case study or conduct interviews as well as the lack of construction companies with successful EMS implementation.

The twenty papers used are good enough to identify the barriers, motivations, benefits, and environmental performance regarding EMS implementation. In addition to these twenty papers, more environmental management papers and EMS case studies were also reviewed to identify, describe, and provide additional information of the EM practices and methods.

The reviewed papers include topics about the identification of EMS implementation barriers and benefits, the suggestion of EM practices to overcome the implementation barriers and enhance the performance of EMS, and the relationship between EMS implementation and environmental performance among different study cases.

The limitations of this thesis are:

1. Most of the studies use literature review as their methodology. Not using case studies as research methodology can result in the lack of understanding of the implementation strategies, barriers, challenges, and benefits of circular economy in a construction project.

2. The lack of information regarding circular economy in the construction industry. Circular economy is a new concept trying to be implemented, therefore not many studies can be reviewed for theoretical background.

3. The time frame of the study is a limitation considering that circular economy focuses on the reusing and recycling of building materials after the life cycle of a building. The life cycle of a building is normally 50 years. This study considers the implementation of circular economy in the design phase of the life cycle, meaning the results will be obtained after the life cycle is done to confirm is the circular economy strategies worked.

4. The construction industry has many different types of projects, meaning the construction procedures vary from each other. Having so many different construction processes result in the lack of a standardized procedure to adapt the concept of circular economy. This study is focusing merely on buildings.

2. LITERATURE REVIEW

This section provides the relevant content for the development of this master’s thesis by studying and analyzing the concept, characteristics, strategies, indicators, and assessment of circular economy in the construction industry.

Circular economy is an economic system that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value always, distinguishing between technical and biological cycles (Kubbinga et al., 2018). As mentioned in the study, this new economic model seeks to ultimately decouple global economic development from finite resource consumption.

The same study also defines circular economy as a new economic model for addressing human needs and fairly distributing resources without undermining the functioning of the biosphere or crossing any planetary boundaries. This highlights the importance of operating within the safe zone of the environment while making sure that minimal social standards are met.

In another study, circular economy is defined as a guide for more sustainable business models, presenting companies with possibilities for closing their material and energy flows (Ren et al., 2020). If implemented correctly in an organization, circular economy enables both business success and the regeneration of the environment.

According to Ren et al. (2020), companies with a circular economy are given the opportunity to reduce tangible costs such as material usage and waste disposal, through resource recovery initiatives, as well as intangible costs such as the potential negative (or lower) reputation of companies that disregard sustainable practices.

2.1 Circular Economy in the Construction Industry

The EU plans to promote the transition to a more circular economy, where the value of products and materials is maintained in the economy for as long as possible, thus minimizing the production of waste and reducing/avoiding the extraction of new resources (Gervasio and Dimova, 2018). Figure 2 shows the circular economy concept suggested by Aguiar et al. (2019).

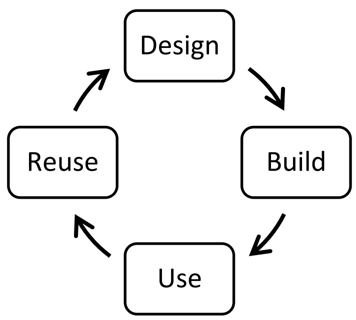

Figure 2 Circular Economy Concept adapted from (Aguiar et al., 2019)

2.1.1 Benefits of CE in the Construction Industry

The construction industry has been prompted to adopt the concept of the circular economy in a bid to reduce the volume of waste generation, preserve natural resources, reduce demand for landfill and improve environmental sustainability. The key objectives of circular economy regarding the construction industry are to avoid waste at the design stage, minimize waste generation during construction, preserve the quality and value of materials during operation, and to ensure reusing or recycling of building components and material at the end of the lifespan (Ganiyu et al., 2020).

As stated by Akhimien et al. (2020) the transition from linear economy into circular economy in the construction industry is not feasible until circular economy principles are applied into the life-cycle stages of buildings, which is a proactive design approach to manage buildings from cradle to grave.

In addition, Akhimien et al. (2020) also define circular economy in buildings as a regenerative closed loop system which is achievable through an appropriate design, accommodating maintenance, recycling, or reuse. In the literature review carried out by this study, it was constantly noticed that there were several attempts to reduce waste, which is one of the major features of resource efficiency.

The implementation of circular economy in the built environment has vast benefits owing the potential to reduce the ecological and carbon footprint of the construction industry. The adoption of circular economy ensures an intergenerational availability of resources by closing (reuse, remanufacture, and recycle), slowing (repair and maintenance), and narrowing (reduce and resource optimization) the loop of resources (Mhatre et al., 2020).

According to Hossain et al. (2020) the following aspects are crucial for adopting circular economy in the construction industry:

- Use of sustainable and durable materials.
- Adoption of design for disassembly.
- Usage of modular and prefabricated elements.
- Development of recovery schemes.
- Establishment of relevant requirements for waste and demolition plans.
- Standards to ensure quality of the recycled materials.
- Technical performance, recycling rate, and traceability of building materials.
- Provision of guidelines and training for demolition companies.

2.1.2 Challenges of CE in the Construction Industry

The two main barriers in the construction sector towards the circular principles are the lack of appropriate design methodologies to enable a better use of C&DW (Construction and Demolition Waste) and the lack of cooperation between the long chain of stakeholders in the construction process (Gervasio and Dimova, 2018). The lack of standardized methods and practices to help them implement circular economy in the construction projects is also highlighted by (Benachio et al., 2020).

The adoption of circular economy in the construction industry presents a challenge as buildings and infrastructure are complex composite structures that usually are designed to last for a longer time span as compared to other products (Mhatre et al., 2020).

2.2 Circular Economy Characteristics

The performance characteristics of circular economy are listed and described in the study carried out by Kubbinga et al. (2018). These 7 characteristics account for the optimal use of materials, energy, and water resources, while it also supports positive impacts on biodiversity, human culture and society, health and wellbeing and the creation of multiple forms of value.

1. Materials are incorporated into the economy in such a way that they can be cycled at continuous high value.
2. All energy is based on renewable sources.
3. Water is managed in a 100% circular fashion.
4. Biodiversity is structurally supported and enhanced.
5. Human society and culture are preserved.
6. The health and wellbeing of humans and other species are structurally supported.
7. Human activities generate value in measures beyond just financial.

The study defines the performance characteristics as the 7 pillars of the circular economy. These circular economy characteristics ensure both positive natural and social impacts. To achieve a positive impact, it is necessary to follow circular economy strategies. Figure 3 shows the 7 pillars of circular economy.

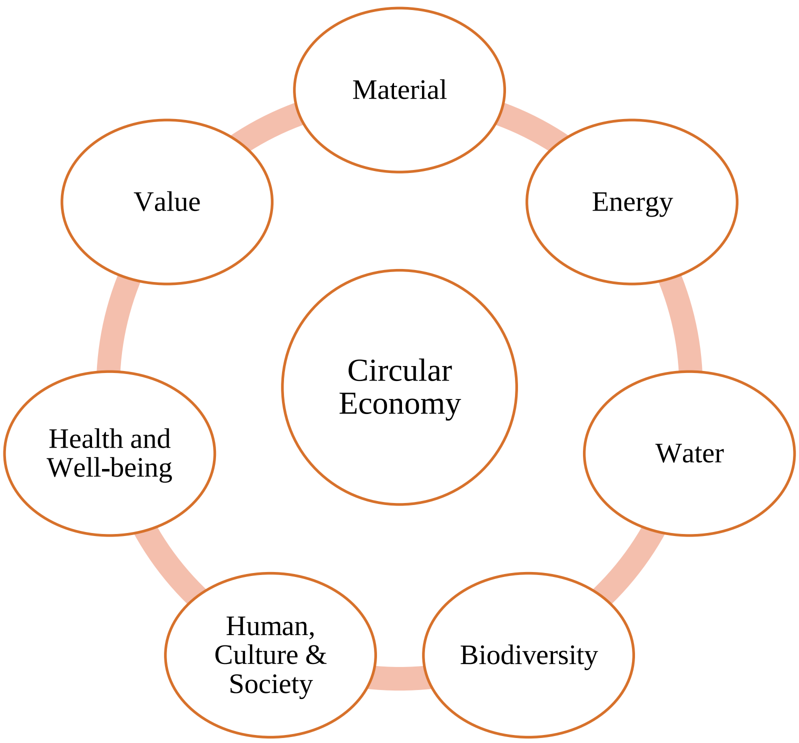

Figure 3 7 pillars of circular economy adapted from (Kubbinga et al., 2018)

A circular economy has its unique characteristics and requirements that makes it distinct from other forms of economy, especially the traditional linear economy. Ganiyu et al. (2020) summarized the key characteristics of a circular economy as:

1. Customer's ability to pay performance or service without ownership.

2. Innovative business models, from transactions to relationship via services and solution models.

3. Reverse cycles that include partners outside current value chains.

4. Innovations for material, component, product reuse, products designed for disassembly and serviceability.

2.3 Circular Economy Strategies

The general strategies according to Kubbinga et al. (2018) for a circular economy are the following:

- Prioritize regenerative resources:
  Ensure renewable, reusable, non-toxic resources are utilized as materials and energy in an efficient way.
- Preserve and extend what it is already made:
  While resources are in-use, maintain, repair, and upgrade them to maximize their lifetime and give them a second life through take-back strategies when applicable.
- Use waste as a resource:
  Utilize waste streams as a source of secondary resources and recover waste for reuse and recycling.
- Rethink the business model:
  Consider opportunities to create greater value and align incentives that build on the interaction between products and services.
- Design for the future:
  Account for the systems perspective during the design process, to use the right materials, to design for appropriate lifetime and to design for extended future use.
- Incorporate digital technology:
  Track and optimize resource use and strengthen connections between supply chain actors through digital, online platforms and technologies that provide insights.
- Collaborate to create joint value:
  Work together throughout the supply chain, internally within organizations and with the public sector to increase transparency and create joint value.

Similarly, the strategies for circular economy as stated by Moraga et al. (2019) are the following:

- **Strategy 1:** preserve the function of products or services provided by circular business models such as sharing platforms. (refuse, rethink, reuse)
- **Strategy 2:** preserve the product itself through lifetime increase with strategies such as durability, reuse, restore, refurbish, and remanufacture.
- **Strategy 3:** preserve the components of a product through the reuse, recovery and repurposing of parts.
- **Strategy 4:** preserve the materials through recycling and downcycling.
- **Strategy 5:** preserve the embodied energy through energy recovery at incineration facilities and landfills.
- **Strategy 6:** measure the linear economy as the reference scenario or the absence of a preservation strategy to show the status, progress, or regress towards CE.

2.4 Circular Economy Indicators

The GRI (Global Reporting Initiative) standards provide a holistic framework that evaluates the economic, environmental, and social performance of an organization. These performance evaluation helps to determine the sustainability of the organization. Indicators give information on the economic, environmental, and social performance or impacts of an organization related to its material aspects. GRI provides 9 economic, 34 environmental, and 48 social indicators (GRI, 2013).

The environmental dimension of sustainability is concerned with the organization's impact on living and non-living natural systems, including land, air, water, and ecosystems. The environmental indicators evaluate impacts related to inputs (such as energy and water) and outputs (such as emissions, effluents, and waste). In addition, it covers biodiversity, transport, and product and service-related impacts, as well as environmental compliance and expenditures (GRI, 2013).

The economic dimension of sustainability is concerned with the organization's impact on the economic conditions of its stakeholders, and on economic systems at local, national, and global levels. Lastly, the social dimension of sustainability is concerned with the impacts the organization has on the social systems within which it operates (GRI, 2013).

The indicators selected by Kubbinga et al. (2018) are used to demonstrate or measure if and how a general strategy for circular economy is put into practice. The indicators are divided into 7 impact areas, which are taken from the seven characteristics of circular economy described in section 2.2. The seven impact areas are the following:

1. Material
2. Energy
3. Water
4. Biodiversity and ecology
5. Human, Culture and Society
6. Health and Well-being
7. Multiple forms of Value

The following 15 indicators are selected in the study. Some of these indicators have already been included in the BREEAM (Building Research Establishment Environmental Assessment Method) guidelines and the study also considers which new indicators could be added to make the standard more circular.

Reduce amount of materials

- A feasibility study is performed on the possibilities of building refurbishment, possibly excluding the option of new development.
- A feasibility study is performed on the possibilities of minimizing the square meters of development (both new construction and renovation), within the specified requirements.
- A feasibility study is performed on the possibilities of minimizing the total material mass used within the specified requirements and square meter surface of development.

Design for reassembly

- De/re-mountable connections are used when placing /installing the product in its direct surrounding, of which the preservation of similar quality can be guaranteed.
- The product is assembled through de-/remountable connections, of which the preservation of similar quality can be guaranteed.
- The connections used for placing/installing the product in its (direct) environment are accessible.

Maximize amount of reused and renewable materials

- The score calculated by the tool MCI (Material Circularity Indicator) is equal or higher than X.
- When determining the materialization, search for local supply of reusable/secondhand materials.
- Recyclable materials are used in the technical cycle.
- Biobased materials are used in the biological cycle.

Knowledge development and sharing

- A building material passport is composed and maintained during the use cycle of the building regarding material cycles.
- The building material passport is available for every building stakeholder.
- Upon completion, the building is delivered with demolition specifications and disassembly guidelines.
- No materials from the C2C Banned List of Chemical Materials are used.
- Building products have no or minimal VOC (Volatile Organic Compounds) emissions.

The concept of circular economy and its application have been extensively explored as shown in several journal papers, the definition of tools and criteria measuring “circularity” of products, companies or regions are not well-defined. The development of indicators for measuring progress of the circular economy initiatives should be a high priority for stakeholders (Rincón-Moreno et al., 2021). The indicators in the study are the following:

Production and consumption

- Self-sufficiency for raw materials
- Percentage of CE procurement
- Generation of waste per € (kg/€)
- Percentage of generation of waste per material consumption.
- Energy productivity (kWh/€)
- Percentage of green energy consumption
- Water consumption productivity (m^3/€)

Waste management

- Percentage of recycling rate of all waste
- Percentage of recycling rate of plastic waste
- Percentage of recycling rate of paper and paper board
- Percentage of circular material use

Competitiveness and Innovation

- Percentage of percentage of CE investment
- Percentage of CE jobs
- Percentage of CE patents

According to Yadav et al. (2020) the CE indicators identified in the study will help the practitioners, policymakers and researchers to draw a framework for adoption of circular, green practices, and sustainable use of resources. The results state that informational, technological, and managerial indicators are of extreme importance in the CE adoption followed by strategy and policy indicators, organizational indicators, and supply chain indicators. The CE indicators identified are the following:

Informational and Technological Indicators

- Adoption of innovative practices
- Advanced technological transfer and applicability
- Penetrating social media and big data analytics within the organization
- Effective facility layout decision making
- Constant monitor on changing market needs
- Effective information management system

Managerial indicators

- Effective planning & management for CE adoption
- Top management commitment for CE adoption
- Allocation of financial budgets
- Sustainable resource management
- Sustainable participation of stakeholders
- Building brand image

- Economic and social benefits of CE

Strategy and policy indicators

- Adopting industrial ecology initiatives
- Availability of CE oriented framework
- Redesign based on customer feedback
- Effective life cycle analysis
- Rewards and incentives for greener activities
- Identifying performance measures for CE
- Supportive government policies

Organizational indicators

- Adoption of 6 R’s
- Employee empowerment and motivation
- Multi-stage quality check system
- Focused training for CE adoption
- Effective inventory management
- Reduction in carbon emission

Supply Chain Indicators

- Coordination and collaboration among SC members
- Supplier commitment for recyclable materials
- Adopting reverse supply chain practices
- Adopting green practices
- Educating customers for CE practices

Circular economy is turned into defined action plans supported by specific indicators. The study tries to understand what do these CE indicators measure. The study proposes a framework to categorize indicators according to the CE strategies and the measurement scope (Moraga et al., 2019).

The classification framework includes quantitative micro scale indicators from literature and macro scale indicators from the European Union ‘CE monitoring framework’. Most of the indicators focus on the preservation of materials, with strategies such as recycling. The CE indicators selected are the following:

1. Self-sufficiency for raw materials
2. Green public procurement
3. Waste generation
4. Food waste
5. Recycling rates
6. Recycling / recovery for specific waste streams
7. Contribution of recycled materials to raw materials demand
8. Trade in recyclable raw materials

9. Private investments, jobs and gross value added
10. Patents related to recycling and secondary raw materials

The study by De Pascale et al. (2020) proposes 61 indicators for measuring circular economy. The indicators are gathered from 137 articles published from 2000 to 2019. The indicators are classified into micro (company), meso (industry), and macro (country). This study only considers the 27 indicators for the micro level considering the methodology of this research. The 27 micro indicators for evaluating circular economy are the following:

1. Disassembly Effort Index
2. Circular Economy Toolkit
3. End-of-Life Index
4. Recycling Indicator Set
5. Reuse Potential Indicator
6. CE Index
7. Material Circularity Indicator
8. Recyclability Benefit Rate
9. Eco-cost Value Ratio
10. CE Indicator Prototype
11. Synthetic Economic Environmental Indicator
12. Longevity Indicator
13. Material Reutilization Score
14. Recycling Index
15. Circular Economy Performance Indicator
16. Product-level Circularity Metric
17. Value-based Resource Efficiency Indicator
18. End-of-life Indices
19. Recycling Desirability Index
20. Sustainable Circular Index
21. Global Resource Indicator
22. Circularity Design Guidelines
23. Combination Matrix
24. Effective Disassembly Time
25. Ease of Disassembly Metric
26. End-of-use Product Value Recovery
27. Circularity Calculator

In contrast with the previous studies, Padilla-Rivera et al. (2021) propose an approach to identify key social indicators for circular economy. The study selected 43 social indicators from a survey to CE experts arriving at a consensus regarding the social measures that are required in a project. After a qualitative (Delphi) and quantitative (fuzzy logic) analysis, the most important social indicators are the following:

1. Decent work and economic growth
2. Responsible consumption and production
3. Good health and well-being
4. No poverty
5. Zero hunger
6. Peace, justice, and strong institutions
7. Reduced inequities

2.5 CO2 Emissions Calculation

This study analyzes how to calculate CO2 emissions and recyclability in a building since they are two of the most important indicators in sustainability. CO2 emissions will tell us the environmental performance of a material and the recyclability indicator will tell us to how extend we can reuse or recycle a material. By using these two indicators along with the support of other additional indicators we can determine if a building is sustainable and if their materials or structural components are recyclable.

Sun and Park (2020) calculated the CO2 emissions during the construction process of a 10-m tunnel. The authors used Revit software to create the 3D model of the tunnel and obtain material information. The authors investigated the related CO2 emission factors for each type of material and analyzed the CO2 emissions of the materials as well as the equipment used in the construction process.

A different study by Syngros et al. (2017) identifies the basic construction materials of four typical houses in Greece and estimates their environmental impact in terms of Embodied CO2 (ECO2). ECO2 is estimated by multiplying material masses with the corresponding ECO2 coefficients (kgCO2/kg). Due to lack of a comprehensive database in Greece, data from an international database is utilized. The Inventory of Carbon and Energy (ICE) is utilized.

The ICE is a free international database that provides the embodied energy and carbon values for a large variety of building materials. Embodied carbon comes from the consumption embodied energy consumed to extract, refine, process, transport and fabricate a material or product (including buildings). It is often measured from cradle to (factory) gate, cradle to site (of use), or cradle to grave (end of life). The embodied carbon footprint is therefore the amount of carbon (CO2 or CO2e emission) to produce a material (Jones, 2019). It contains data for over 200 materials, broken down into over 30 main material categories, such as:

- Bricks
- Cement
- Concrete
- Glass
- Timber
- Plastics
- Metals

- Minerals and stone

2.6 Recyclability Indicator

Several studies have proposed methods to quantify the recyclability of materials. The study by (WRAP, 2008) proposes a recyclability indicator by weight and by value.

- Recyclability by weight

X tons of product A can be recycled to product B, during this process Y tons of material are lost. The recyclability by mass is:

$$\left(\frac{X - Y}{X}\right)\%$$

Equation 1 Recyclability by weight

- Recyclability by value

Product A is installed into a building and costs €X/ton. Depending on how it is fixed Product A can be reprocessed into Product B for a cost of €Y/ton. Product B when made from virgin materials has an installed value of €Z/ton. Recyclability by value is:

$$\frac{Z - Y}{X}$$

Product A is installed into a building and costs €X/ton. Product A can be recovered and reprocessed into product B, which has a value of €Y/ton. Recyclability by value is:

$$\frac{Y}{X}$$

Villalba et al. (2002) determine a recyclability index (R) for materials. It is defined as how much of the original properties lost during use (measured by D) a material can reacquire (measured by G). It will be defined by the following equation:

$$R = 1 + G - D$$

$$G = \frac{V_P - V_R}{V_M} \ and \ D = \frac{V_M - V_R}{V_M}$$

$$R = 1 + \frac{V_P - V_R}{V_M} - \frac{V_M - V_R}{V_M}$$

$$R = \frac{V_P}{V_M}$$

Equation 2 Recyclability by value

Where:

Vm = value of material in first production or virgin. (€/ton)

Vr = value of material after use. (€/ton)

Vp = value of material after it is recycled. (€/ton)

Zampori et al. (2016) propose the Circular Footprint Formula (CFF). Recycling, energy recovery, as well as using secondary materials and energy leads to questions in Environmental Footprint work on how to quantify for benefits and burdens of these processes.

$$CFF = (1 - R_1)E_V + R_1\left\{AE_{recycled} + (1 - A)E_V * \frac{QS_{IN}}{Q_P}\right\} + (1 - A)R_2\left(E_{recyclingEoL} - E_V^* * \frac{QS_{OUT}}{Q_p}\right) + (1 - B)R_3(E_{ER} - LHV * X_{ERheat} * E_{SEheat} - LHV * X_{ERelec} * E_{SEelec}) + (1 - R_2 - R_3) * E_D$$

Equation 3 Circular footprint formula

Where:

A = allocation factor of burdens and benefits between supplier and user of recycled materials.

B = allocation factor of energy recovery processes. It applies both to burdens and benefits.

QSin = quality of the ingoing secondary material.

QSout = quality of the outgoing secondary material.

QP = quality of the virgin material.

R1 = proportion of material in the input to the production that has been recycled from a previous system.

R2 = proportion of the material in the product that will be recycled (or reused) in a subsequent system. R2 shall therefore consider the inefficiencies in the collection and recycling (or reuse) processes. R2 shall be measured at the output of the recycling plant.

R3 = proportion of the material in the product that is used for energy recovery at EoL.

Erecycled = specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting, and transportation process.

ErecyclingEoL = specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting, and transportation process.

Ev = specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

E*v = specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

EER = specific emissions and resources consumed (per functional unit) arising from the energy recovery process.

Eseheat and Eseelec = specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat, and electricity.

ED = specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the End of Life of the analysed product, without energy recovery or other usable product output.

X ERheat = the efficiency of the energy recovery process for heat.

X ERelec = the efficiency of the energy recovery process for electricity.

LHV = lower heating value of the material in the product that is used for energy recovery.

Vefago and Avellaneda (2013) propose the hierarchy of recyclability for building materials. In the design stage of a new building, the masses that will be reused, recycled, infraused, infracycled and the non-renewable virgin materials will be calculated. The total mass is added to determine the mass percentage for each category. The resulting figures are added, yielding as a final percentage value between 0 and 100. If all the materials are non-renewable virgin materials, then the index of recyclability will be 0. On another hand, a value that equals 100 means that all the products used in the building came from previous building constructions. Figure 4 shows the pyramid to evaluate the recyclability of a building.

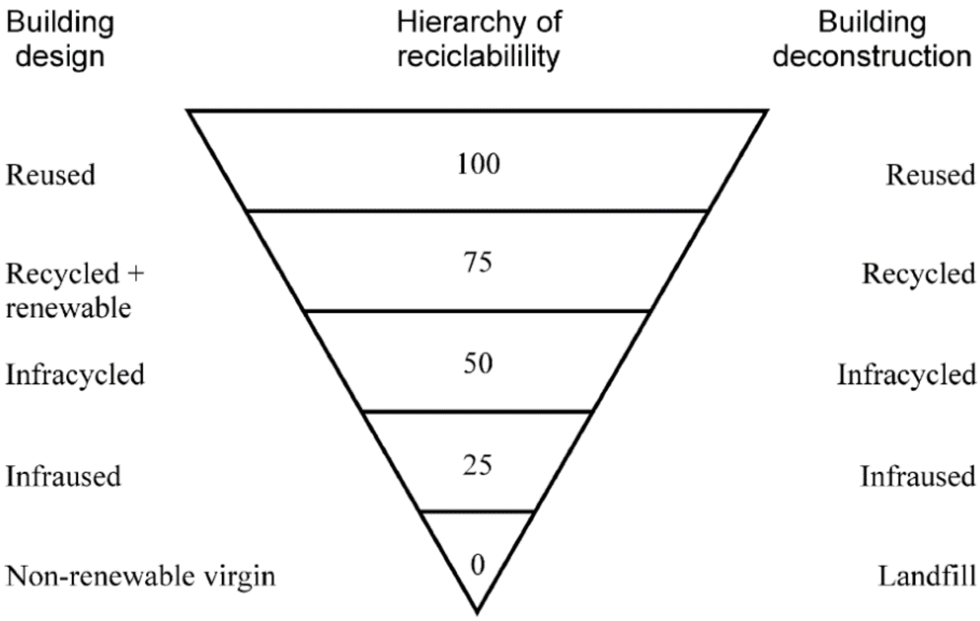

Figure 4 Hierarchy of recyclability extracted from (Vefago and Avellaneda, 2013)

The One Click LCA is an easy and automated life cycle assessment software that helps you calculate and reduce the environmental impacts of your projects, products, and portfolio. One Click software has compatibility with many structural design software such as Revit, Tekla, Rhino & Grasshopper, and SketchUp (One Click LCA, 2021). The website proposes three ways for evaluating circularity in a building:

1. Choose material sources

A circular building uses more recycled, renewable, or reused resources, and fewer virgin materials. You can easily decide the sources of the materials by entering the recycled, renewable, or reused percentages corresponding with a material. This information does not influence the LCA results but is used to document material circularity.

2. Design out waste

Select different end-of-life processes for the materials in the BIM model. By default, materials will have an end-of-life process assigned. These processes are based on the material type, and you will notice that there will be differences in the end-of-life processes depending on what material options you use. Consider material installation using Design for Disassembly practices, e.g. using dismountable fasteners instead of glue or if it allows otherwise non-destructive removal of the material. Design so that material is adaptable for future changes in the use of the building.

3. Measure circularity

Quantify and assess the circularity of materials in your design with a building circularity score. The circularity score of the building is evaluated from 0 to 100%. Compare different design scenarios and find the most circular option. Figure 5 shows the building circularity analysis.

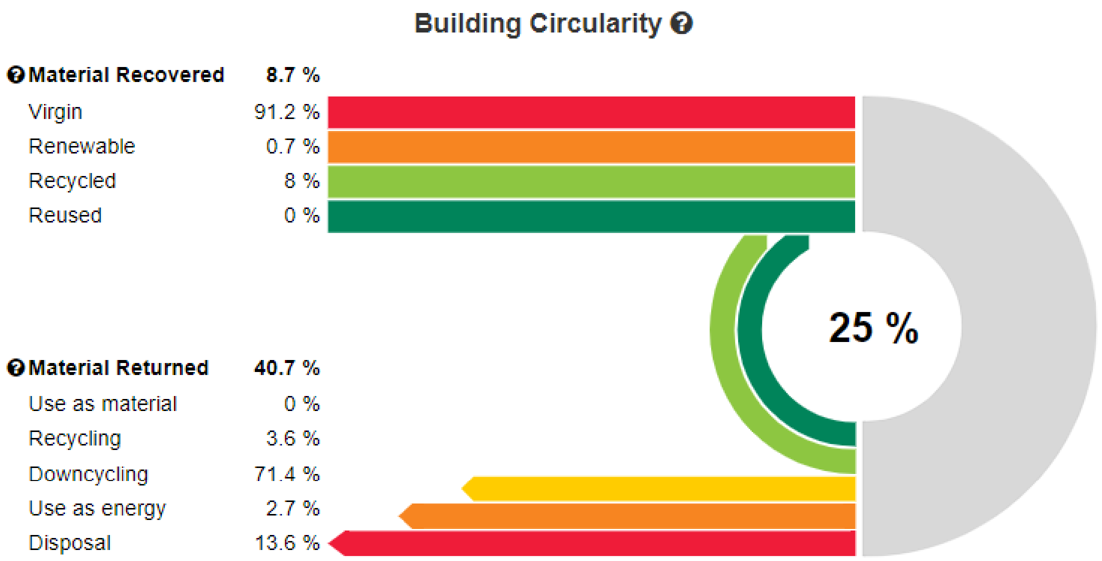

Figure 5 Building circularity OneClick LCA extracted from (One Click LCA, 2021)

2.7 Circular Buildings

A circular building is developed, used, and reused without unnecessary resource depletion, environmental pollution, and ecosystem degradation. It is constructed in an economically responsible way and contributes to the wellbeing of its inhabitants and surroundings. Technical elements are demountable and reusable, and biological elements can also be brought back into the biological cycle (Kubbinga et al., 2018). Similarly, Benachio et al. (2020) describe a circular building as a building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with circular economy principles.

Circular buildings ideally contribute to a sustainable built environment in all lifecycle phases. A circular building should provide positive impacts in each of the seven performance characteristics mentioned in section 2.2. A circular building should consider its location in the surrounding area and its spatial characteristics. A circular building is not an indivisible entity, it consists of different layers that can be distinguished as according to the 6S framework developed by Stewart Brand: site, structure, skin, space plan, services, and stuff (furnishing & fittings), that are all part of a circular system of products, components, and materials (Kubbinga et al., 2018).

Also stated by Kubbinga et al. (2018), four practical design strategies for circular buildings can be deduced from the seven general characteristics for circular economy presented in section 2.2. The four design strategies are the following:

1. **Reduce:** design a system that has very low demands for energy rather than trying to figure out how to supply an enormous energy demand in a sustainable way.
2. **Synergize:** design options that satisfy multiple resource demands (such as a greenhouse that can be used to generate heat, electricity, collect water, provide recreational space, and be used to produce food) are preferable to single-solution choices.
3. **Supply:** demands should be supplied using clean, renewable, recycled, or otherwise ecologically beneficial sources.
4. **Manage:** it is important to maintain feedback about how a system is working once it is operational.

2.8 Circular Design

According to Gervasio and Dimova (2018) the following structural design aspects are required in order to achieve an efficient use of resources/materials and minimize the energy consumption throughout the life cycle of a building: design optimization, reduction of construction and demolition waste, design for flexibility and adaptability, durability of materials and components, robustness, resilience, design for deconstruction and disassembly and reuse/re-assembly materials or structural components. Figure 6 shows the structural design aspects over the life cycle of a building.

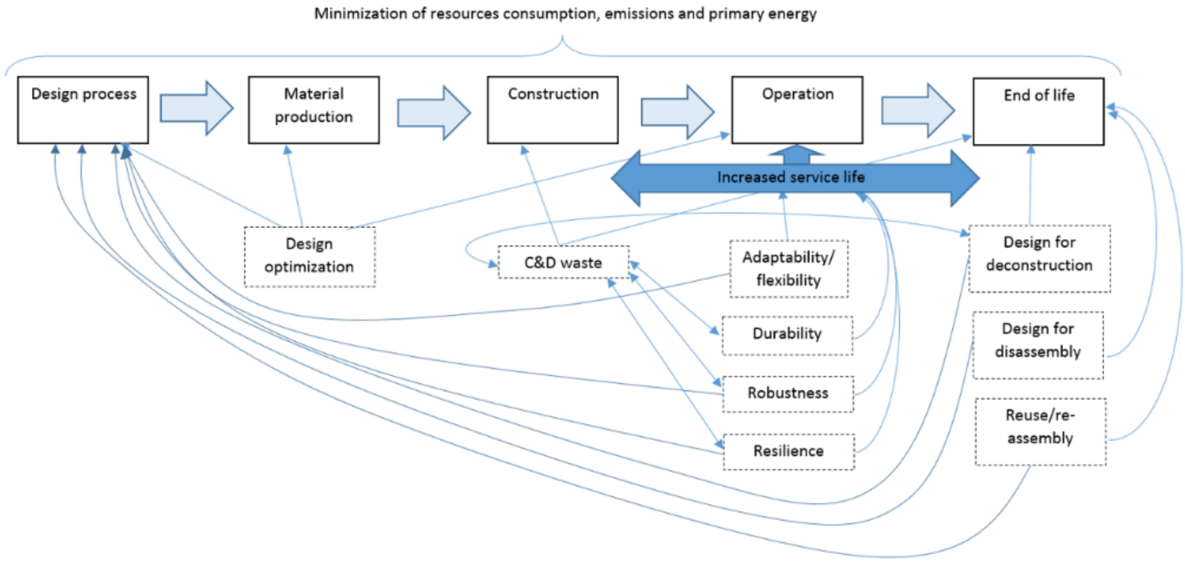

Figure 6 Links between aspects of structural design over the life cycle extracted from (Gervasio and Dimova, 2018)

Figure 6 highlights the pressure that relies on the design process. The earlier these aspects are considered in the design process, the higher is the chance to positively influence the performance of the building over its life span. Benachio et al. (2020) also emphasize the necessity to implement circular economy concepts from the project design phase. The potential to consider those concepts in the earlier stages of a project can help assess the reuse percentage of the materials that will be used and help decision makers choose the most fitting materials in the circularity mentality, as well as better manage all the resources that will be used throughout the life cycle of the building. Each of the structural design aspects mentioned by Gervasio and Dimova (2018) are listed and described as follows:

- **Design optimization:** the selection of materials shall consider the proper use of the mechanical properties of each material and minimizing the use of them. This may include the use of mew materials to improve the structural behavior (composite materials, FRP, glass, high strength steel, high strength concrete, etc.) and/or the use of materials with recycling content.

- **Reduction of construction and demolition waste:** the C&D waste shall be reduced to a minimum and the residues that are unavoidable should be recycled or reused. Emphasis should be given to new construction methods and technologies such as lightweight construction, modular construction, prefabrication, and industrial construction.

- **Design for flexibility and adaptability:** consider future change of use or requirements in the design process to extend the life span and to prevent the building to get obsolete with consequent demolition.

- **Durability of materials and components:** the durability of the materials should be considered to minimize maintenance and avoid the need for replacement.

- **Robustness:** the ability of a structure to withstand unforeseen events, without being damaged to an extent disproportionate to the original cause, is of particular importance in places prone to hazard events and to face potential higher loading demands due to climate change and/or terrorism actions.

- **Resilience:** the capacity of the structure to adapt to and easily recover from hazards, shocks, or stresses without compromising long-term prospects is of particular importance in places prone to hazard events or other unforeseen events.

- **Design for deconstruction and disassembly:** the way the structure is demolished has extreme influence on the amount and quality of materials and/or structural components that can be further use in another structure, consequently avoiding the need to produce new materials from virgin materials. The way structural elements are connected influence the way they are disassembled.

- **Reuse/re-assembly materials or structural components:** the further use of materials and/or structures components should consider the quality of the materials and an estimation of their remaining service life.

Similarly to Gervasio and Dimova (2018), the study developed by Akhimien et al. (2020), identified the following seven aspects or themes for the implementation of a circular economy in buildings. The seven aspects are listed and described as follows:

1. **Design for disassembly:** building design consideration for easy building deconstruction. Use of prefabricated modules in the context of assembly and disassembly. Modular design, design for disassembly, design for adaptability, design for deconstruction, standardization.
2. **Design for recycling:** building design program from inception for recyclability. Reuse, recycling of building components, and reduction of construction waste.

3. **Building materiality:** building materials analysis and selection as a major consideration for a circular economy. Material selection and recyclability.

4. **Building construction:** building construction methods that can help facilitate the application of circular economy.

5. **Building operation:** building in use and modalities for operation in line with circular economy principles.

6. **Building optimization:** optimization of building parts for durability and longevity. Repair activities, upgrades, and component exchange to improve the durability and performance of a building.

7. **Building end of life:** building end of life program and loop systems. Interventions to either restore, reuse, recycle a building's components.

As stated by (C2C Products Innovation Institute, 2021), circular design encourages us to rethink business models, how we make products, and to consider the system surrounding them, but we also need to think about the materials we use. Whether it's improving the safety of users or ensuring that resources can be used again and again. The Cradle to Cradle Products Innovation Institute is dedicated to powering innovation for the circular economy through the development and creation of products that have a positive impact on people and planet. Through the cradle to cradle certified products, the institute sets the global standard for products that are safe, circular, and are made responsibly.

Designing whole buildings with an eye toward circularity and retaining value requires a shift in thinking as well as in process. The challenge is about ensuring the value of the building will be retained in the future. From a design perspective, it is necessary looking at buildings as layers and examining the building process and the supply chain in reverse. There must be a change of approach in the design process, considering what products are available from other buildings instead of designing without material restriction. A key component for circular design is documentation. It is important to identify what products are in the building, what are the products made of, and how they can be safely re-integrated into a supply chain for reuse (C2C Products Innovation Institute, 2021).

Design for disassembly is a fundamental principle for circular design modifying decisions and material choices, changing how materials are joined and how they are layered in a way that is accessible, reversible, and robust. The goals for design for disassembly are to create enduring buildings and projects, create value for building owners, and eliminate waste with closed loops. The result are more flexible buildings that are easy to repair, refurbish, or reconfigure; buildings that function as material banks; and products and materials that retain value and return to productive use at end of life (C2C Products Innovation Institute, 2021).

2.9 BIM and Circular Economy

Buildings contain a lot of materials. The high value of reusing building components has not been adopted yet on a large scale because of several reasons, one of them being poor building information management (Aguiar et al., 2019).

BIM (Building Information Modelling) has the capability of storing different types of information in its digital model, becoming an important tool for the adoption of circular economy in the built environment (Benachio et al., 2020). The study by Ganiyu et al. (2020) identifies several key areas where BIM capabilities could help in achieving the circular economy in construction include: automatic clash detections, design error reduction, an early collaboration of stakeholders, visualization, simulation of waste performances, waste management reporting, among others.

As defined by Aguiar et al. (2019), BIM is often referred to as a 3D model where all information is stored. Around the globe BIM is gaining rapid visibility within the construction industry and governments are starting to demand and even mandate BIM deliverables. One of these BIM deliverables is known as a material passport, which is a document with information about the materials used in a building and can be an important method to promote circular design.

A material passport is a tool that registers all the necessary information about the materials used in a building and measures its impact on the four values of circular construction: health, cyclability, residual value, and productivity (Construcia, 2021). The material passport helps to identify, quantify, locate materials and products in the construction space for their correct recovery at the end of the cycle of use. According to the Spanish construction company these are the benefits of implementing a material passport:

- The building is converted into an open source for the extraction of materials that can be re-used indefinitely, with the maximum quality possible.
- Waste is prevented.
- The extraction of raw materials is reduced.
- Problems associated with the toxicity of materials and changes in future regulations are prevented.
- It maintains the value of materials, products, and components over time.
- Incentive to the supply chain to produce sustainable and circular construction materials and products.
- Facilitates for developers and directors the selection of sustainable and circular construction materials.
- It promotes inverse logistics and the recovery of products, materials, and components.

A material passport allows the traceability of the materials, indicates their location in the building and the best way of extracting them. It also includes a manual of deconstruction specifying the channels of cyclability available to ensure the recovery of the raw materials and their value (Construcia, 2021).

Additionally, but no less important, it also estimates the economic value of each material according to the planned channels of recovery and analyses the possible alternatives. Circular construction would not be feasible without this tool. The material passport helps with the decision-making regarding the selection of materials and the level of circularity of the buildings (Construcia, 2021).

Material passports can be used to store important data of these building components for their use in their end of life, helping incorporate the materials in the circular loop, instead of disposing them. The existence of a consolidated BMP (Building Material Passport) can help the evaluation and optimization of recycling potential and environmental impacts (Benachio et al., 2020).

The main objective of the research carried out by M. Honic et al. (2019) is to generate a BIM-based Material Passport for the optimization of the building design regarding resources use and documentation of materials, thereby using BIM as knowledge base for geometry and material properties and coupling to further databases for assessment of ecologic footprint and recycling potentials. The study proposes a workflow for the compilation of a MP.

The BIM-based MP has diverse roles along a building`s lifecycle. In early design stages it serves as an optimization tool, whereby in later stages it acts as a documentation and inventory of building stocks. During the research, several obstacles were faced, such as lack of standards and structures for material properties in material databases.

BIM software and a similar methodology as M. Honic et al. (2019) is also used by Meliha Honic, Kovacic, Sibenik, et al. (2019) for modelling and the Material Inventory and Analysis Tool Building One (BO) is used for data management. BO is a database used for gathering relevant data from BIM and eco-databases and carrying out the MP assessments. Figure 7 shows the BIM methodology for the generation of a material passport.

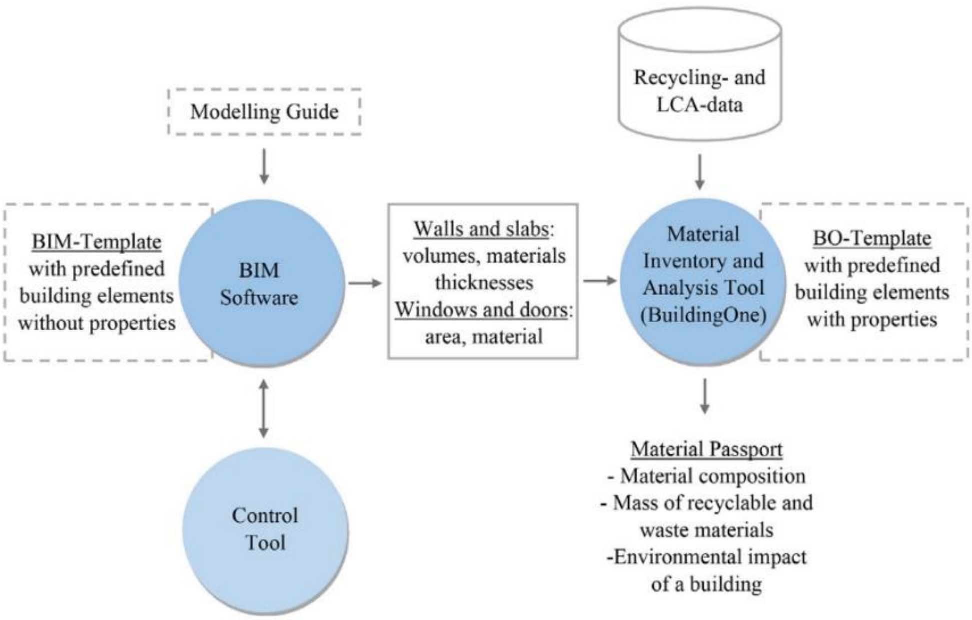

Figure 7 BIM methodology for the generation of Material Passports extracted from (Meliha Honic, Kovacic, Sibenik, et al. 2019)

Following the material passport concept by M. Honic et al. (2019), a different study by the same authors Meliha Honic, Kovacic, and Rechberger (2019) tries to identify if the recycling potential of buildings can be improved with the use of material passports in an Austrian residential building. Figure 8 shows the scheme of the material passport for this case. The building is divided into four levels:

1. **Building Level:** consists of the mass and the share of all materials in the entire building.
2. **Component Level:** the sum of all materials existing in a particular component.
3. **Element Level:** materials of one element and where each element is identified.
4. **Material Level:** the mass, type of connection with the enclosed materials, and the recycling potential is described for one specific layer/material.

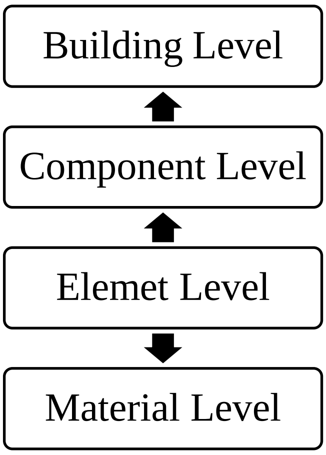

Figure 8 Scheme of the Material Passport adapted from (Meliha Honic, Kovacic, and Rechberger, 2019)

The proposed methodology by Meliha Honic, Kovacic, and Rechberger (2019), consists of coupling building catalogues and eco-repositories to digital design tools. Eco2soft is a tool from the Austrian Institute for Building and Ecology, usually utilized to carry out Life Cycle Assessments for building and considers the following indicators: lifespan, density, recycling weight, GWP (Global Warming Potential), AP (Acidification Potential) and PEI (Primary Energy Intensity). The last three indicators GWP, AP and PEI, are given as kgCO2/kg eq. for GWP, kgSO2/kg eq. for AP, and MJ/kg for PEI. Figure 9 shows the methodology for the compilation of the material passport.

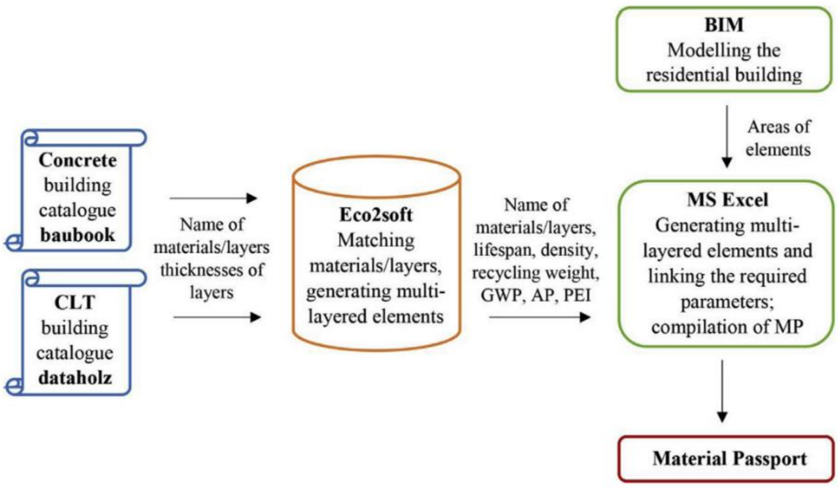

Figure 9 Methodology for the compilation of the Material Passport extracted from (Meliha Honic, Kovacic, and Rechberger, 2019)

Figure 10 shows the material passport created for one element (outside wall 1) of the building. The material passport includes layers/materials, lifespan, thickness, density, recycling weight, GWP, AP, and PEI. The material passport is done for a variant of the building made of concrete and another one made of timber.

Table 1
Outside wall 1 - input data, Variant A.

Layers/Materials	Lifespan [years]	Thickness [m]	Density [kg/m^3]	Recycling weight [1–5]	GWP [kgCO_2 eq./kg]	AP [kgSO_2 eq./kg]	PEI [MJ/kg]
Cross Laminated Timber	60	0.024	440	1	−1.103	0.0023	8.02
Sawn Timber (10%) (battens)	50	0.040	540	1	−1.405	0.0006	1.86
Wood Fiberboard	50	0.022	250	3	−0.154	0.0112	14.01
Wood Fiberboard Insulation	50	0.200	160	3	−0.804	0.0040	15.55
Cross Laminated Timber	100	0.095	440	2	−1.103	0.0023	8.02
Sawn Timber (10%) (battens)	60	0.060	540	1	−1.405	0.0006	1.86
Rockwool (90%)	50	0.060	33	4	1.935	0.0141	23.19
Gypsum Plaseterboard	60	0.025	850	3	0.192	0.0007	4.68
Area: 1897.08 m^2		**0.466**					

Figure 10 Material passport for a building element extracted from (Meliha Honic, Kovacic, and Rechberger, 2019)

The study by Meliha Honic, Kovacic, and Rechberger (2019) concludes that a material passport serves not only as design-optimization tool, but moreover as an inventory of embedded materials, thus representing an essential aid for the implementation of the Urban Mining strategy. The MP consists of qualitative and quantitative knowledge of the material composition of, and the material distribution within a building structure and gives the possibility to evaluate the embedded materials of a building according to the mass, recycling potential, and environmental impacts. The significant advantage of a MP is that it can be compiled in early design stages, where changes with a high impact can be conducted at low cost.

The material passport is the connection between information and the element/material. It must contain information on quality, safety, sustainability, use and operation, disassembly, reuse potential, history of checks and traceability of materials (Munaro et al., 2019). The following information must be included in a material passport feasible to the wood frame constructive system:

1. **General data:** product name, composition, manufacturer, supplier, use period, use recommendation, performance characteristics, and technical data.
2. **Security measures:** security information, toxicological recommendations, handling and storage instructions, risk identification, and fire protection.
3. **Sustainability:** environmental declaration, Life cycle assessment (LCA), LCA boundaries, methodology, results, and interpretation.
4. **Use and operation:** positioning and location in the building, connections details, assembly instructions, maintenance, and cleaning.
5. **Disassembly guide:** disassembly, transportation, and storage instructions.
6. **Reuse potential:** end-of-life considerations (reuse, recycling, and remodeling) and, disposal options.
7. **History:** use period, verifications made during use, latest operations, and updates during operations.
8. **Other information:** standards used and complementary material.

2.10 Feasibility Study

A feasibility study provides an accurate assessment of the factors which might affect a project. A feasibility study evaluates a project and analyses both the positive and negative aspects. It evaluates both internal readiness and external opportunities available to successfully complete a project. The purpose of a feasibility study is to determine if a business opportunity is possible, practical, and viable. It provides a structured method to focus on problems, identify objectives, evaluate alternatives along with associated benefits and costs, and aid in selecting the best solution for the project (Gardiner, 2005).

Circular economy strategies and product development should be considered in the feasibility study of a construction project to achieve better reusability and recyclability of the building. Luz et al. (2018) propose the integration of Life Cycle Analysis into the product development process to develop a new product with better characteristics and reduce its environmental impacts. Carmona Marques et al. (2019) state that Life Cycle Analysis for Product Development concerns with concept design, such as eco-concepts, eco-design, and design environment. It deals with material selection, packaging design and alternatives during the design phase of the product. The study by Luz et al. (2018) proposes the following product development process:

1. Planning
2. Conceptual Design
3. Detailed Design
4. Testing/Prototype
5. Production/Market Launch
6. Product Review

Durmusoglu and Kawakami (2021) identified that Information Technology (IT) enhances the success of New Product Development (NPD) in a company. According to the study, IT improves NPD performance in all the three different stages: discovery, development, and commercialization. As mentioned in the previous sections by several journal papers, a good information database and an adequate model have great importance in implementing and successfully achieving circular economy. This is also where the use of a BIM software is highlighted as previously stated in section 2.9. Additionally, Panizzon et al. (2020) mention the main determinants for the ability of developing new products. the determinants are the following: Learning Capability, Organizational Creativity, International Entrepreneurial Orientation, Reconfiguration Capability, and Technological Capability.

The study by Bao and Li (2020) proposes a new paradigm of construction. The study investigates the feasibility of a Lego-inspired construction. Inspired by Lego blocks that can be assembled via dry joints and disassembled for reuse in different structures. The blocks are made using a bendable concrete, aiming to assemble various structures with dry joints. As stated by (C2C Products Innovation Institute, 2021) in section 2.8, there must be a shift on how materials are joined and how they are layered in for a better disassembly. Figure 11 shows the concrete blocks used for the Lego inspired construction.

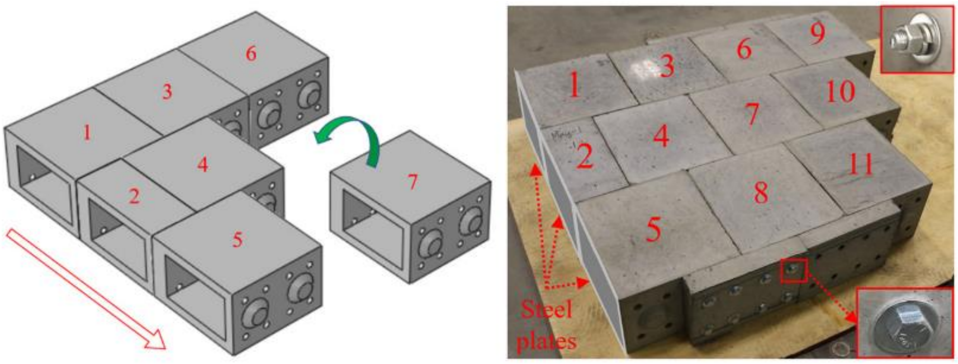

Figure 11 Lego inspired concrete blocks extracted from (Bao and Li, 2020)

Figure 12 shows the concrete blocks assembled for the construction of a footbridge. Figure 13 shows the demonstration of reconfigurability: reusing the same concrete blocks from the footbridge to assemble a part of a building frame. Figure 12 and 13 illustrate the shift that must be taken on how materials are joined and how they are layered in for circular economy.

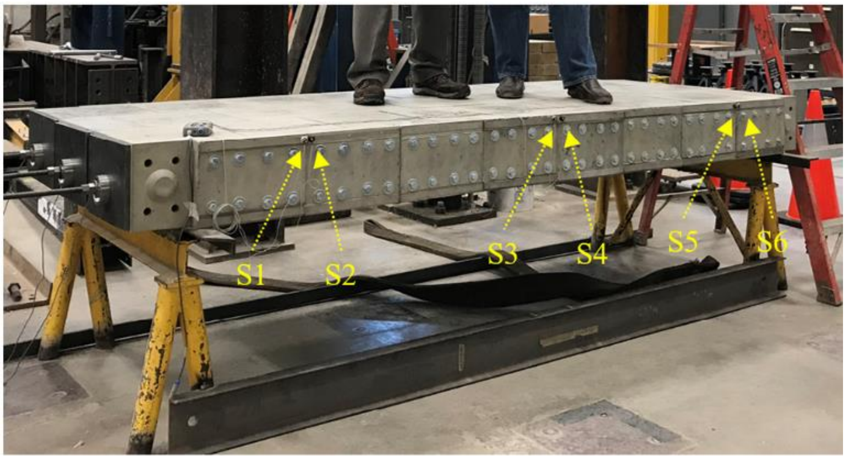

Figure 12 Footbridge assembled with concrete blocks extracted from (Bao and Li, 2020)

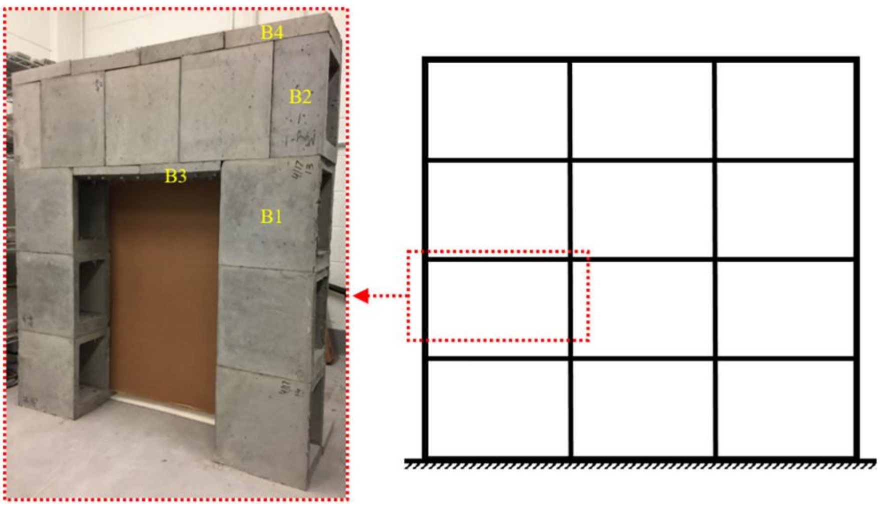

Figure 13 Part of a building frame extracted from (Bao and Li, 2020)

3. RESEARCH METHODOLOGY

This section presents the research methodologies followed by the twenty studies analyzed in the literature review. Table 1 shows the twenty journal papers and the research methodologies they have used. This allows us to comprehend what approach have other studies been taking to do research on circular economy in the construction industry. Identifying the methodologies is useful to analyze is previous methodologies have been showing successful results or if there is a need to change methodologies to obtain better or newer results.

Table 1 Research methodology by the journal papers

Studies		Research Methodology
1	Aguiar et al. (2019)	Literature review
2	Akhimien et al. (2020)	Literature review
3	Alencar et al. (2020)	Literature review
4	Bao and Li (2020)	Experiment
5	Benachio et al. (2020)	Literature review
6	Carmona Marques et al. (2019)	Literature review
7	De Pascale et al. (2020)	Literature review
8	Durmusoglu and Kawakami (2021)	Questionnaire survey
9	Fořt and Černý (2020)	Experiment (Life Cycle Assessment)
10	Ganiyu et al. (2020)	Literature review
11	Gervasio and Dimova (2018)	Experiment (Life Cycle Assessment)
12	Honic et al. (2019)	Case study
13	Honic, Kovacic, and Rechberger (2019)	Case study
14	Honic, Kovacic, Sibenik et al. (2019)	Case study
15	Hossain et al. (2020)	Literature review
16	Kubbinga et al. (2018)	Literature review
17	Luz et al. (2018)	Literature review
18	Mhatre et al. (2020)	Literature review
19	Moraga et al. (2019)	Literature review
20	Munaro et al. (2019)	Case study
21	Ortiz et al. (2009)	Literature review
22	Padilla-Rivera et al. (2021)	Delphi method
23	Panizzon et al. (2020)	Questionnaire survey
24	Ren et al. (2020)	Literature review
25	Rincón-Moreno et al. (2021)	Case study
26	Sun and Park (2020)	Case study
27	Syngros et al. (2017)	Case study
28	Vefago and Avellaneda (2013)	Experiment
29	Villalba et al. (2002)	Experiment
30	Yadav et al. (2020)	Experiment (Best Worst Method)

Table 2 and Figure 14 show the results of the research methodologies used by the 30 journal papers. The five methods used by the 30 journal papers are: literature review, case study, experiment, survey, and delphi method. Table 2 and Figure 14 help us understand the tendencies of the researchers in recent years. The results also help future studies to decide what research method they want to use to provide a different approach of what is being done now.

Table 2 Research methodology summary

Research Methodology	
Literature Review	14
Case Study	7
Experiment	6
Survey	2
Delphi Method	1
Total	30

As presented in Table 2, most of the studies (14) have selected a literature review to conduct their research. While a literature review provides a good background of the existing literature it does not provide new ideas or suggestions on how to apply the theory of circular economy to a real building. This study has selected a case study as research methodology to provide the construction industry with a more practical approach on how to implement the circular economy concept in the building design process.

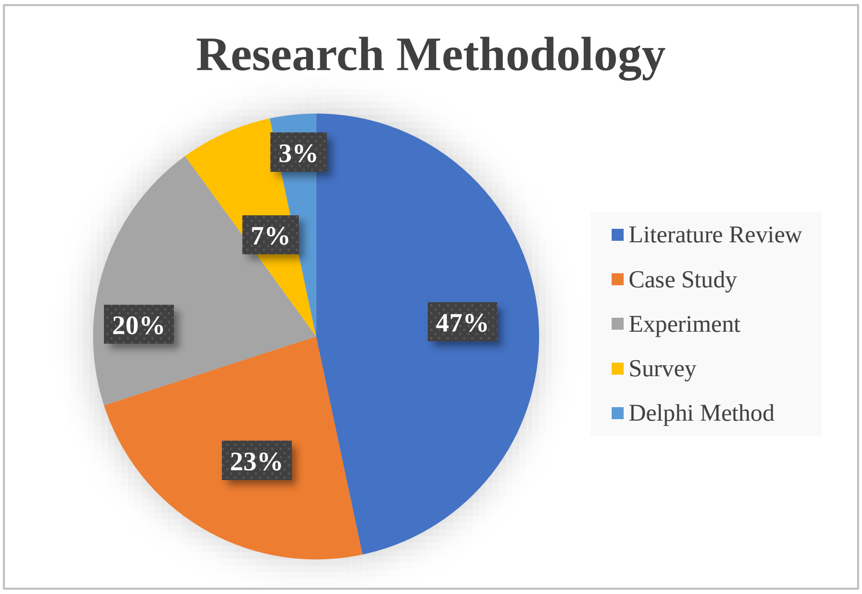

Figure 14 Research methodology

As observed in Figure 14, the application of a case study is only used 23% of the time. This study considers the case study methodology highly important because it shows how to apply the knowledge to a real situation and what to learn from this implementation.

Table 3 shows all the journal papers analyzed in this study and the main subject they researched. Column 1 shows the list of the 30 journal papers used in the literature review of this study. Column 2 shows the main subject the journal papers were doing their research on. This table helps understand what topics are being studied the most and what topics need to be considered more. Doing research about the same topics does not help expanding the academic knowledge.

Table 3 Subjects researched by the journal papers

Subject Researched		
Studies		Subject
1	Aguiar et al. (2019)	Circular design
2	Akhimien et al. (2020)	Circular economy principles
3	Alencar et al. (2020)	Sustainability in construction
4	Bao and Li (2020)	Product development
5	Benachio et al. (2020)	Circular economy implementation
6	Carmona Marques et al. (2019)	Product development
7	De Pascale et al. (2020)	Measuring circular economy
8	Durmusoglu and Kawakami (2021)	Product development
9	Fořt and Černý (2020)	Transition to circular economy
10	Ganiyu et al. (2020)	BIM competencies
11	Gervasio and Dimova (2018)	Life Cycle Assessment
12	Honic et al. (2019)	BIM based material passport
13	Honic, Kovacic, and Rechberger (2019)	Material passports potential
14	Honic, Kovacic, Sibenik et al. (2019)	Material passport framework
15	Hossain et al. (2020)	Circular economy characteristics
16	Kubbinga et al. (2018)	Circular buildings
17	Luz et al. (2018)	Product development
18	Mhatre et al. (2020)	Circular economy in built environment
19	Moraga et al. (2019)	Circular economy indicators
20	Munaro et al. (2019)	Material passport feasibility
21	Ortiz et al. (2009)	Sustainability in construction
22	Padilla-Rivera et al. (2021)	Circular economy indicators
23	Panizzon et al. (2020)	Product development
24	Ren et al. (2020)	Circular economy as a driving force
25	Rincón-Moreno et al. (2021)	Circular economy indicators
26	Sun and Park (2020)	CO_2 emissions calculation
27	Syngros et al. (2017)	Embodied CO_2 emissions
28	Vefago and Avellaneda (2013)	Recyclability index
29	Villalba et al. (2002)	Recyclability of materials
30	Yadav et al. (2020)	Circular economy indicators

Table 4 and Figure 15 show the results of the main topics or subjects researched by the 30 journal papers. Column 1 shows all the topics and column 2 shows the amount of journal papers who did research on this topic.

Table 4 Categories of the topics researched by the journal papers

Topics Researched	
Circular economy	11
Product development	5
Material passport	3
CO_2 emissions	2
Recyclability	2
Sustainability	2
Circular design	2
BIM	2
Life cycle assessment	1
Total	30

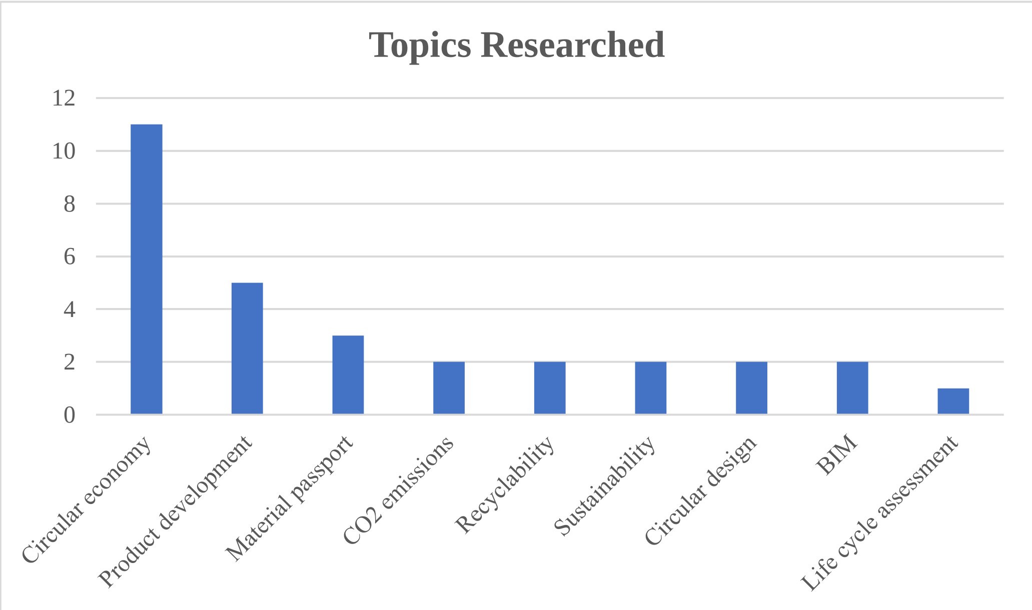

Figure 15 Topics researched by the journal papers

As presented in Figure 15, most of the journal papers did most of their research on the topic of circular economy. This is understandable since this is the topic of interest for this study. By analyzing Figures 14 and 15, it can be observed that most of the studies doing research on circular economy had literature review as their research methodology, which highlights the need of case studies to understand the application of circular economy in a construction project. The use of literature review methodology can result in redundant and useless information.

4. CIRCULAR ECONOMY IN THE BUILDING DESIGN PROCESS

This section provides the framework and the CE strategy to implement for the adoption of circular economy in the building design process. The methodology used in this study is the application of the framework and CE strategy to a BIM case study in Norway.

4.1 Description of BIM Model

The building is in Bogafjell, Norway. It is a small district with approximately 7,448 inhabitants and located in the south west region of the country. The construction for Bogafjell Ungdomsskole (Junior High School) started in October 2018, the school was completed by the start of school year in 2020. Due to steep mountain terrain, the building consists of 4 floors.

The school has a capacity of 504 students, a net area of 9.35 m² per student. The budget for the construction project was NOK 262.8 million approximately USD 30.6 million. The school has 18 classrooms for normal teaching and extra rooms for teaching electives and foreign languages. It has an area of 5500 m². The building is certified as a low-energy building.

The building for the case study is a four-floor school made of concrete and steel, additionally the school has a pedestrian bridge made of steel and retaining walls on the sides made of reinforced concrete. The BIM model provided by the Norwegian consulting company Multiconsult consists only of the structural components of the project (footings, columns, beams, slabs, and roof). The foundations are made of reinforced concrete. The interior columns are made of steel and the exterior columns are made of reinforced concrete. The beams are made of steel. The slab system used in the project is a hollow core slab made of prestressed concrete. The roof is supported on steel beams and consists of corrugated steel panel and rockwool. Figure 16 shows a picture of the building.

Figure 16 Picture of the building extracted from *(Bogafjell Ungdomsskole, 2021)*

To provide a better comprehension of the building and the BIM model that is used in this study Figures 17 to 20 show different perspectives of the school.

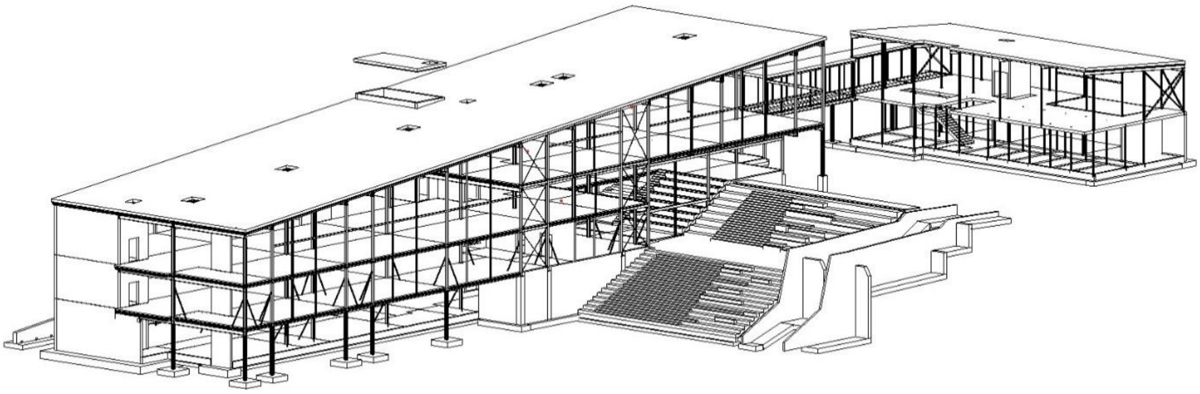

Figure 17 Left front side of the school

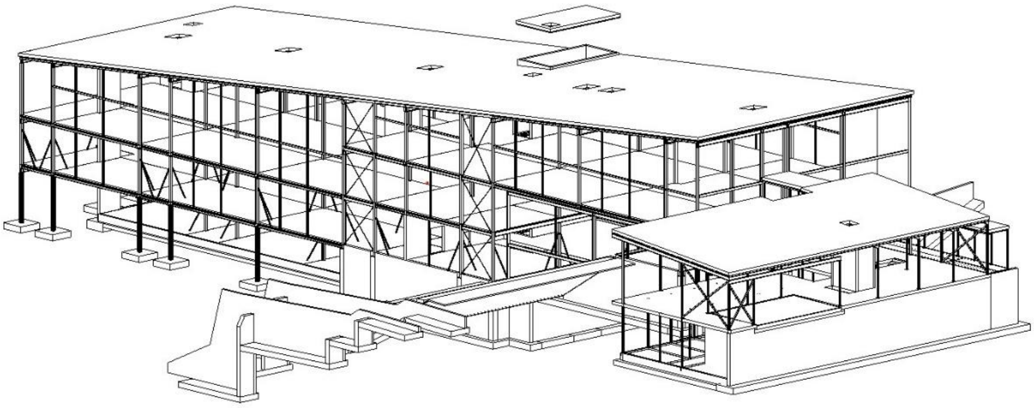

Figure 18 Right front side of the school

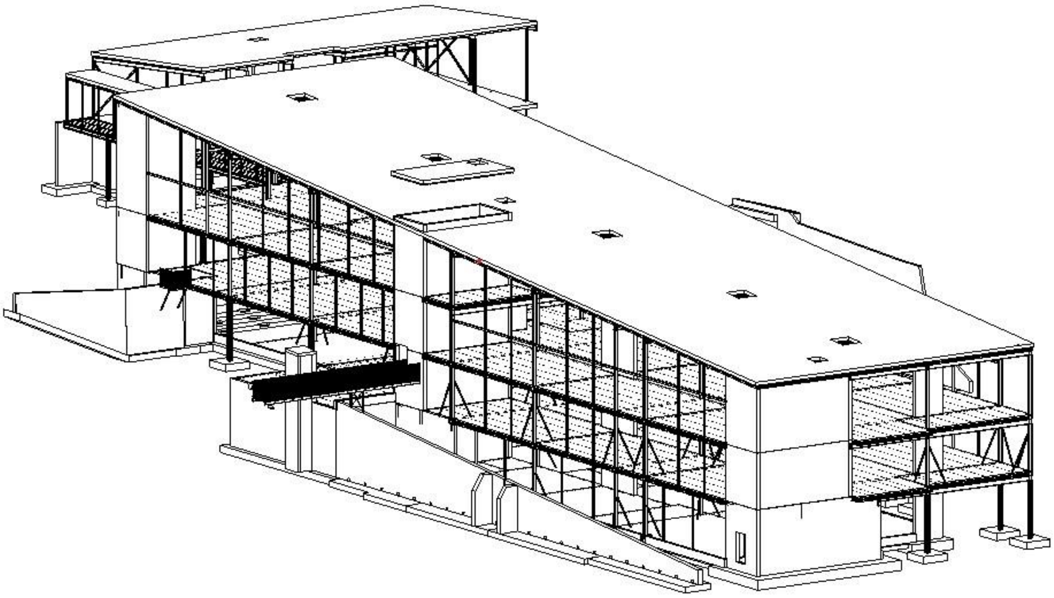

Figure 19 Left back side of the school

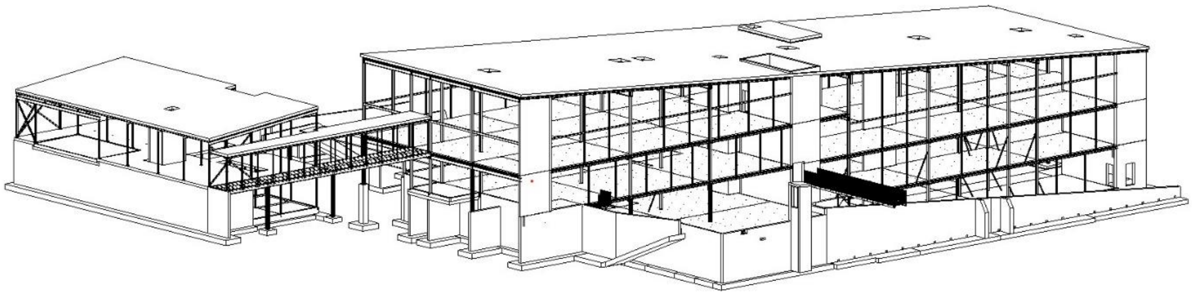

Figure 20 Right back side of the school

4.2 CE Framework in the Building Design Process

Figure 21 shows the framework this study will follow for the implementation of CE in the building design process. The studies presented in section 2.9 develop a material passport from the end-of-life point of view. These MPs analyze the recyclability of the materials in a building once the building is designed and completed. This study tries to create a new material passport from the design phase point of view, which will be called Design Passport (DP). The Design Passport will help the structural engineers decide what materials and structural components are better to build a Circular Building. This will be done by considering the CE structural design aspects mentioned and described in section 2.8 as well as the CE Indicators for these aspects in section 2.4.

In the early stage of the circular economy framework, a feasibility study must be included. The feasibility study comprises the requirements of the stakeholders for the project, decision on what type of materials to use, special requirements, a cost-benefit analysis of the products, and product development. This feasibility study will help the construction companies have a better selection of their materials and products for the implementation of circular economy. The initial selection of the proper materials is highly important to achieve a better reusability or recyclability at the end of the life cycle of any building.

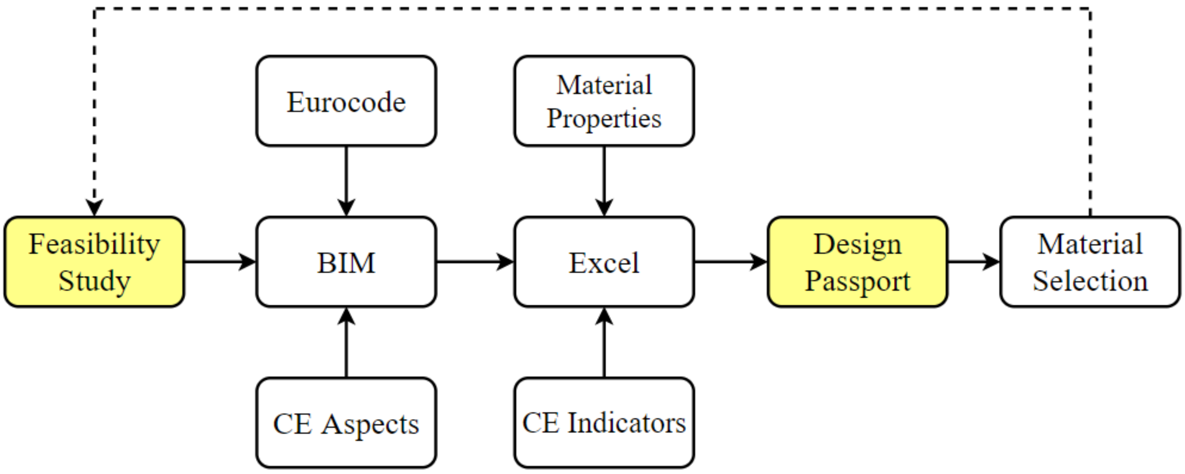

Figure 21 Framework for CE in the building design process

4.3 Categorization for CE Aspects

The implementation of circular economy in the building design process starts by categorizing the structural design aspects proposed by two studies. Table 5 shows the structural design aspects needed according to both studies to achieve circular economy in the building design process. Study 1 was carried out by Gervasio and Dimova (2018) and Study 2 by Akhimien et al. (2020).

Table 5 Categorization of CE Structural Design Aspects

Categorization of CE Structural Design Aspects		
	Study 1	Study 2
1	Design optimization	Design for disassembly
2	Reduction of construction and demolition waste	Design for recycling
3	Design for flexibility and adaptability	Building materiality
4	Durability of materials and components	Building construction
5	Robustness	Building operation
6	Resilience	Building optimization
7	Design for deconstruction and disassembly	Building end of life
8	Reuse/re-assembly materials or structural components	

This study categorized the 8 aspects from Study 1 and the 7 aspects from Study 2 into 3 structural design aspects. The categorization was made according to the similarities between the two studies and grouping the aspects that had a similar meaning between each other. The 3 categories for the CE structural design aspects are the following:

1. **Design Optimization:**

The selection of materials shall consider the proper use of the mechanical properties of each material and minimizing the use of them. This may include the use of new materials to improve the structural behavior (composite materials, FRP, glass, high strength steel, high strength concrete, etc.) and/or the use of materials with recycling content. The durability of the materials and structural components should be considered to assure the robustness and resilience of the building, minimize maintenance operations, and avoid the need for replacement.

The material selection for the case study seems to be appropriate for the needs of the project. No new composite material was utilized in the project. Considering new composite materials could reduce the weight of the structure or improve the performance of the building. New compositions like TCC (Timber Concrete Composite) or using new advanced concrete admixtures (self-diagnosis, self-healing, self-curing, and self-protection admixtures) could provide a lighter and more sustainable building.

Self-diagnosis admixture consists of self-sensing and self-diagnosis of mechanical stress, strain, cracking and other damages of concrete. Self-healing admixture consists of self-repair of cracks combined with increased corrosion resistance and durability. Self-curing admixture consists of shrinkage reduction during early age that will contribute in improving service life through complete mitigation of autogenous shrinkage. Self-protection admixture consists of lowering permeability, improving resistance to high temperature fatigue, improving resistance to operate under low temperatures, higher resistance to chloride transport, and corrosion protection. The main expected benefits of the advanced admixtures are the following:

- Reduced maintenance costs and extended service life.
- Increased sustainability of the infrastructures through reduced repair cycles and reduced risk of accident due to material failure.

2. **Design for Disassembly and Adaptation**

The way a structure is demolished has extreme influence on the amount and quality of materials and/or structural components that can be further use in another structure, consequently avoiding the need to produce new materials from virgin materials. The way structural elements are connected influence the way they are disassembled. Building design process should consider easy building deconstruction. Emphasis should be given to new construction techniques such as, lightweight construction, modular construction, prefabricated modules, and industrial construction.

The case study uses conventional construction techniques meaning it will complicate the disassembly of structural components at the end of the life cycle. The use of steel for the beams and steels facilitates the disassembly of these components and facilitates the reuse of them in a different project of the company. Recovering a complete structural component increases the savings the company could achieve instead of recycling the steel. The concrete components used for the slab system cannot be recovered due to its construction system. The only option will be demolishing the slabs and using the concrete residue as fine or coarse aggregate for another project. There is also a high probability that the supporting beams will be damaged in the demolishing process and they cannot be recovered for further reuse.

Consider future change of use or requirements in the design process to extend the life span and to prevent the building to get obsolete with consequent demolition. As mentioned in the paragraph before, the construction method should facilitate the removal and addition of new structural components if needed. The case study was built as a junior high school. If a change of use would occur in the future, it seems that the school would have to undergo a remodeling construction process. The positive aspect about the school is that few inside concrete walls are observed inside the building. Assuming the use of prefabricated walls, a change of space distribution within the building will be simple.

This study has selected three building products from the Cradle to Cradle Products Innovation Institute that could be applied to the case study to improve the design for disassembly and adaptation of the building. The selected products for the case study are the following:

- Polypropylene Raised Floor: a polypropylene raised flooring solution designed to facilitate changes in the layout of offices, allowing updating of data lines and voice and the free development of communication infrastructure needed to meet business growth. The system includes modular thermoplastic raised floor and structured cabling for voice and data. Figure 22 shows the polypropylene raised floor in an office.

Figure 22 Polypropylene raised floor extracted from *(C2C Products Innovation Institute, 2021)*

- ClickBrick: the self-gripping bricks can be installed with mechanical fasteners rather than chemical connections like mortar, allowing for easy disassembly and reuse in other structures. ClickBrick is not weather dependent and can be laid in all weathers, enabling year-round construction. Figure 23 shows a house with the ClickBrick facade.

Figure 23 ClickBrick façade extracted from *(C2C Products Innovation Institute, 2021)*

- Slimline Building System: the system combines the ceiling, utility space, and subfloor into one prefabricated, panelized system that can be pulled apart and reconfigured as the building's functionality changes or disassembled for reuse in new projects. Mechanicals can be integrated into the hollow floor and remain permanently accessible. Figure 24 shows the slimline building system.

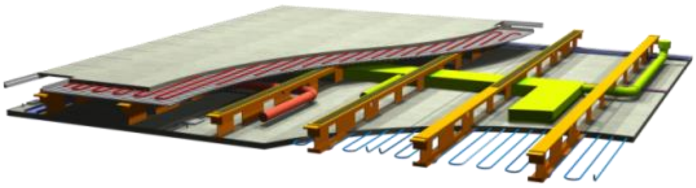

Figure 24 Slimline Building System extracted from *(C2C Products Innovation Institute, 2021)*

Another three products have been selected by this study to assist in the design for disassembly and adaptation from the website (Lindapter, 2021). This clamp connects and fastens steel sections together without the need for onsite drilling or welding. Figure 25 shows examples of the GC girder clamp.

Figure 25 Examples type GC girder clamp extracted from *(Lindapter, 2021)*

The second innovative product is called the Floorfast, which is used for securing steel floor plates. It consists of a malleable iron body casting with a countersunk socket screw; the eccentric stepped web of the casting allows it to lock under the steelwork providing full face contact when torque is applied. Figure 26 shows the FF Floorfast.

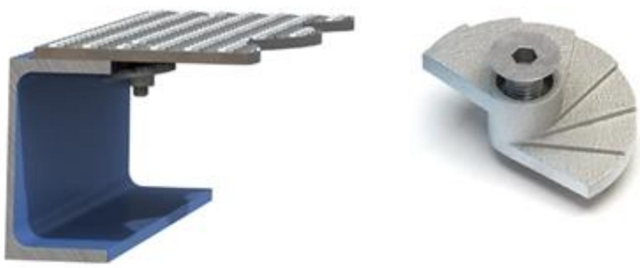

Figure 26 Type FF Floorfast extracted from *(Lindapter, 2021)*

The third product is the Hollo-Bolt, which is suitable for hollow sections, tubes and where access is available from one side only. The Hollo-Bolt is approved by ICC-ES to resist seismic loads and wind loads in all seismic design categories (A to F). It provides corrosion protection with additional JS500 protection as standard or hot dip galvanized. Figure 27 shows the HB Hollo-Bolt.

Figure 27 Type HB Hollo-Bolt extracted from *(Lindapter, 2021)*

3. **End of life Program:**

Construction and Demolition (C&D) waste shall be reduced to a minimum and the residues that are unavoidable should be recycled or reused. Building end of life programs, such as C&D waste management, can provide the tool to reduce the C&D waste of a building.

It is important that a C&D waste management identifies, classifies, and recovers as much materials as possible to reduce their disposal in landfills or incinerators. As mentioned before in the literature review of this study, the use of BIM is of high importance for the company to know the location and amount of materials a building has. As proposed by this study, the Design Passport helps the construction company understanding and simplifying all the information from the BIM model. The Design Passport results in a user-friendly excel sheet since Revit software might not be as easy to use and obtain. Figure 28 shows the construction and demolition waste management process a construction company should follow at the end of the life cycle of a project.

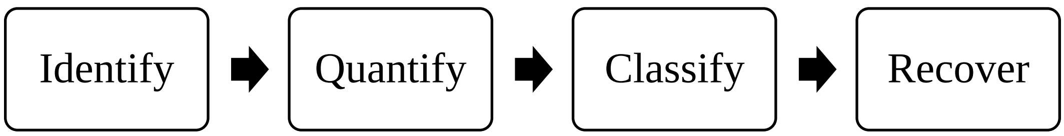

Figure 28 Construction and demolition waste management process

This C&D waste management process will ideally not be needed in the future if the building is completely circular, meaning all its components and products can be disassembled and reused in the different project. The construction industry has not achieved this level of circularity so implementing a waste management plan is necessary to reduce the amount of waste a building generates after demolition.

4.4 Selection of CE Indicators

The indicators to evaluate circularity in the case study are selected from six different studies and the Global Reporting Initiative guideline. These indicators will help the construction companies understand how to evaluate circular economy in the building design process of their own different projects. Figure 29 shows the contribution of all the six studies and GRI to the selection of CE indicators. Table 6 shows the names of the six studies proposing CE indicators in the construction industry.

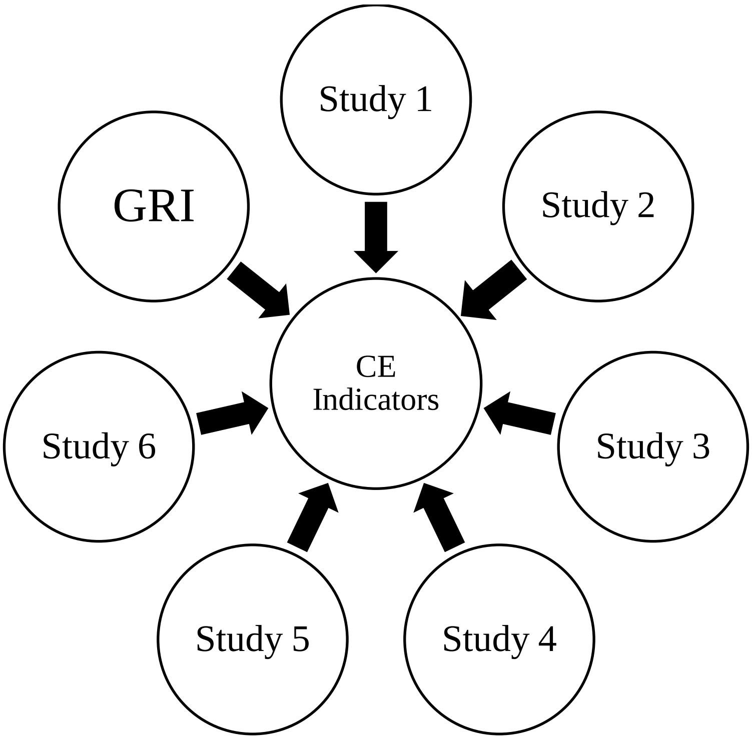

Figure 29 CE Indicators for the case study

Table 6 Studies for the selection of CE Indicators

Studies for the selection of CE Indicators	
Study 1	Kubbinga et al. (2018)
Study 2	Rincón-Moreno et al. (2021)
Study 3	Yadav et al. (2020)
Study 4	Moraga et al. (2019)
Study 5	De Pascale et al. (2020)
Study 6	Padilla-Rivera et al. (2021)

The six studies provided a total of 102 indicators from where to select. The studies and the 102 indicators are listed in Appendix A. This study considers the selection of 3 indicators for each CE aspects selected in the previous section 4.3. The indicators were selected according to their ease of use and understanding for construction companies to implement them. This study also selected quantifiable indicators so that judgement, lack of understanding or explanation from stakeholders does not affect the result. Quantifiable indicators can provide a good evaluation of the materials ability to be reused or recycled as well as its environmental performance. Table 7 shows the selected indicators.

Table 7 Selection of CE Indicators

CE aspects	Indicators
Design Optimization	1. Recyclability (%)
	2. CO2 emissions (kgCO2/kg)
	3. Use of recyclable materials (kg)
Design for Disassembly and Adaptation	4. Demountable connection (yes/no)
	5. Accessible Connection (yes/no)
	6. Disassembly Time (hours)
End of life Program	7. Materials used (kg)
	8. Recycled materials (kg)
	9. Total weight of waste by type and disposal method (kg)

1. Recyclability Index (%)

This study has selected the recyclability by value approach to estimate the recyclability of the case study. This approach was selected due to its simplicity to calculate and understand. The recyclability (R) is calculated with the following equation:

$$R = \frac{V_P}{V_M}$$

Equation 4 Recyclability Index

Where:

Vp = value of material after it is recycled. (€/ton)

Vm = value of material in first production or virgin. (€/ton)

To provide a better comprehension of how recyclable the overall building is, this study utilizes the recyclability pyramid shown in Figure 4. The case study will obtain a final score between 0 and 100%. Ideally the construction companies want their building to achieve 100%, meaning the whole structure is reusable.

2. CO2 emissions (kgCO2/kg)

The CO2 emissions are calculated using the Inventory of Carbon and Energy (ICE) free international database that provides the embodied energy and carbon values for a large variety of building materials. The database provides the kilograms of CO2 for every kilogram of the material. The total kilograms of the materials will be calculated using information from BIM and their known densities.

3. Use of recyclable materials (kg)

This indicator helps understanding how much of the materials, products or structural components that will be used for the construction of a new building have been recycled or are reused from other projects. A construction company will want the weight of recyclable materials (kg) as high as possible. The benefits of using recyclable materials are reflected in the reduction of costs, increase in profit, and a more sustainable building.

4. Demountable connections (Yes/No)

As mentioned before demountable connections are of high importance to disassemble the structural components of a building so that they can be reused instead of having to demolish them. This indicator consists of identifying and listing all the connections in the building and simply saying Yes if they can be disassembled or No. Figure 30 shows a steel column, a steel beam, and a reinforced concrete column connection that can be easily disassembled with the use of steel plates between the elements. The welds can be broken to recover the elements afterwards. The main objective of a demountable connection is to recover all the elements without any damage. Every connection might have its own challenges but all of them should be analyzed to recover as much structural components as possible.

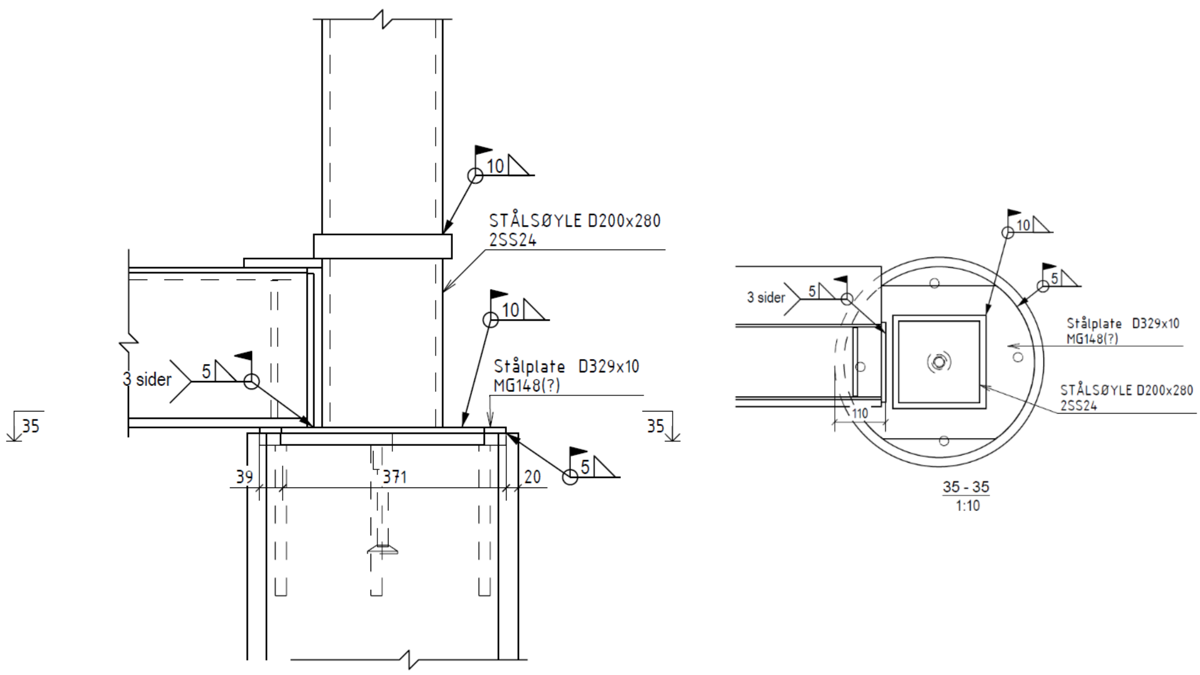

Figure 30 Steel beam, steel column, and a reinforced concrete column connection provided by the consulting company Core Technology

5. Accessible Connections (Yes/No)

The connections in the building must be accessible for the construction workers to disassemble them. Similarly, to indicator number 4, this indicator consists of identifying and listing all the connections in the building and simply saying Yes if they are accessible for construction workers or No, they are not accessible. Figure 31 shows a concrete column - beam connection. A concrete floor is layered on top of the beam, covering all the spaces in between the elements, and hindering accessibility. It means the concrete floor must be demolished first and most probably damaging the elements in the connection before removing the steel plates.

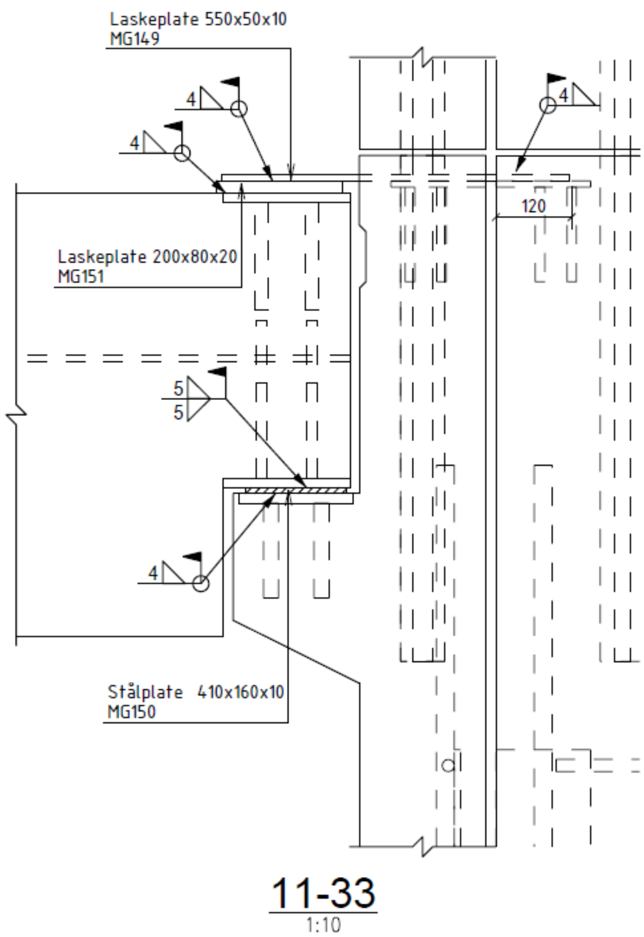

Figure 31 Concrete column - beam connection provided by the consulting company Core Technology

6. Disassembly Time (hours)

This study considers disassembly time an important indicator for implementing circular economy in a building. The disassembly time of the connections will be measured in hours. Every building presents its own challenges and geometry, but this indicator can also be estimated by an experienced worker. In the future construction companies can start recording the disassembly times to create their own database. The construction companies want this indicator to be as low as possible to save time, money, and recover the products faster for further use. Figure 32 shows a concrete column - steel beam connection. The connection is joined by a steel and its disassembly time should be fast by just breaking the welds and releasing the steel beam from the plate.

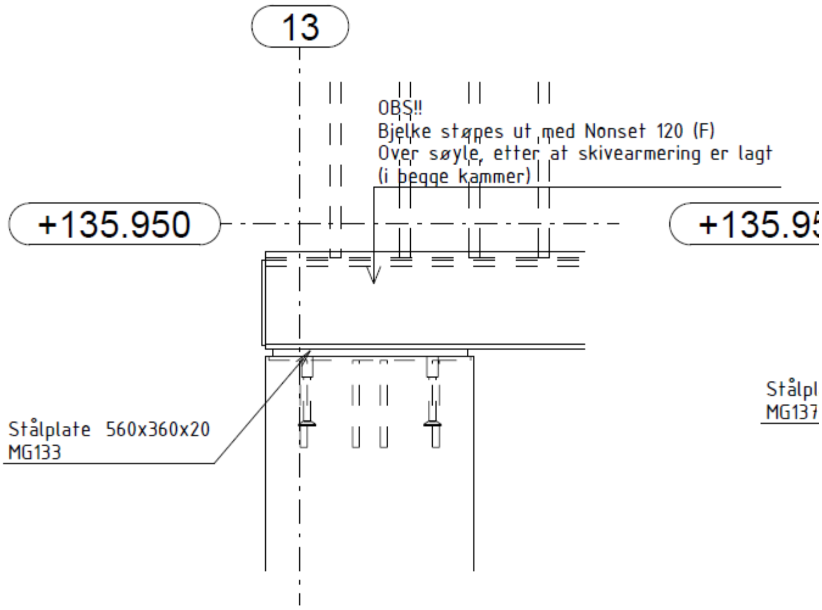

Figure 32 Concrete column - steel beam connection provided by the consulting company Core Technology

7. Materials used (kg)

When the building is completed, it is important for the construction company to have the location and total amount of materials, products or components used. Tools like BIM and the Design Passport proposed by this study can facilitate this calculation and documentation. This information will be needed at the end of the building's life cycle to recover as much materials as possible.

8. Recycled materials (kg)

Due to the lack of circular buildings in the current construction industry, there must be a demolition process at the end of the buildings life cycle. It is important for the construction companies to know how much of the demolished material is going to be recycled. This indicator will be measured by the amount of kilograms the company can recycle from the materials after demolition. Another approach will be calculating the percentage of the recycled material.

9. Total weight of waste by type and disposal method (kg)

As mentioned in the previous section 4.3, having an end of life program such as C&D waste management is of vital importance for the construction companies now since complete circular design has not been achieved yet. Not having complete circularity means there will be waste at the end of the building's life cycle and after the recycling process which is covered by indicator number 8. This indicator helps in the classification of waste by type and the disposal method for this type of waste. The amount of waste will be calculated in kilograms. The goal for the construction companies in the future is to achieve complete circularity with their buildings and eliminate their demolition waste and the use of this indicator.

4.5 Circular Economy Evaluation

The case study provided by Multiconsult contains only the structural components of the building. This study analyses the materials used in the case study which are classified into 5 different types: prefabricated concrete beams used for the slab system, steel beams and columns, reinforced concrete walls, rockwool sheets used for the roof, and timber used on some of the stairs. Figure 33, 34, and 35 show the main structural components used in the school. These elements will be used as representative elements for the application of the CE indicators.

Figure 33 Concrete beam

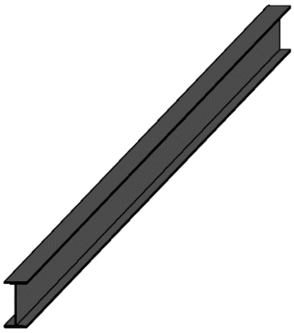

Figure 34 Steel beam

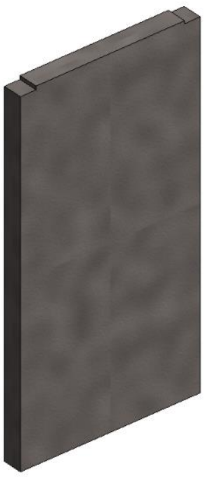

Figure 35 Reinforced concrete wall

As mentioned in section 2.9, the development and implementation of a document with all the information about the materials or components if highly important. This section develops the necessary information for the design passport of the case study. Table 8, 9 and 10 show the application of the first three indicators to the case study. These three indicators are under the Design Optimization category. Indicator 1 is recyclability, indicator 2 is CO2 emissions and indicator 3 is use of recyclable materials.

Table 8 Recycled and First Production Prices

Design Optimization			
Materials		Vp (€/kg)	Vm (€/kg)
1	Steel	0.15	1.38
2	Reinforced Concrete	0.027	0.12
3	Prefabricated Concrete	0.027	0.12
4	Rockwool	0	0
5	Timber	0.015	0.41

Column 1 shows the materials of the building. Column 2 (Vp) is the value of material after it is recycled (€/kg). The price for recycled steel is €0.15/kg. This price was obtained from (Reliable Recycling Center, 2021) located in Maryland, USA. This website provides the prices at which this company buys the different types of steels. The price for crushed concrete is €0.027/kg. This price was obtained from (Home Guide, 2021). This website provides the prices for several construction services and materials in the USA. This study considers the recycled value of rockwool as zero. The price for recycled timber is €0.015/kg. This price was obtained from (Let's Recycle, 2021) in the UK and (Recycling Today, 2021) in the USA. Table 6 shows the recyclability percentage of the project. This method shows how much value of the structural components does a construction company gets back by recycling.

Column 3 (Vm) is the value of material in first production or virgin (€/kg). The price for a steel element is €1.38/kg. The price for reinforced concrete is €0.12/kg. The price for prefabricated concrete is €0.12/kg. The price for timber is €0.41/kg. All the costs for the different elements were obtained from a budget of a construction company in Honduras. The construction company is Banegas Hill y Asociados Ingenieros. Only one element was selected for each material to obtain the cost per kilogram. The elements selected from the budget had similar characteristics to the representative elements shown in Figure 33 to 35. The cost per kilogram of the representative element is used to evaluate the whole weight of the material in the case study. Using the representative elements simplifies the calculation process for this study. As an example, the cost per kilogram of the steel beam element in Figure 34 is used to calculate the entire cost of all the steel elements in the building. Table 9 shows the recyclability index for the case study.

Table 9 Recyclability Index of the Case Study

Design Optimization					
Materials		Weight (kg)	Vp (€)	Vm (€)	Recyclability (%)
1	Steel	155,800.30	23370.05	215004.41	10.87
2	Reinforced Concrete	1,562,363.00	42183.80	187483.56	22.50
3	Prefabricated Concrete	1,981,858.70	53510.18	237823.04	22.50
4	Rockwool	19,704.10	19704.10	-	0
5	Timber	494.30	494.30	202.66	3.66
Total		3,720,220.40			59.53

Column 1 shows the materials of the building. The REVIT model only contains the structural components of the structure. Column 2 shows the total weight of these materials, as it can be observed, most of the structure consists of steel and concrete (prefabricated or reinforced). Column 3 shows the recycled value of the material for the total structure in euros. Column 4 shows the first production value of the materials for the total structure in euros. Column 5 shows the recyclability of the structure in percentage (59.53%). The recyclability index is calculated using Equation 1. The recyclability of the case study is evaluated using Figure 4 presented in section 2.6 and classifies the structure as Recycled. Figure 36 shows the classification of the case study using Figure 4.

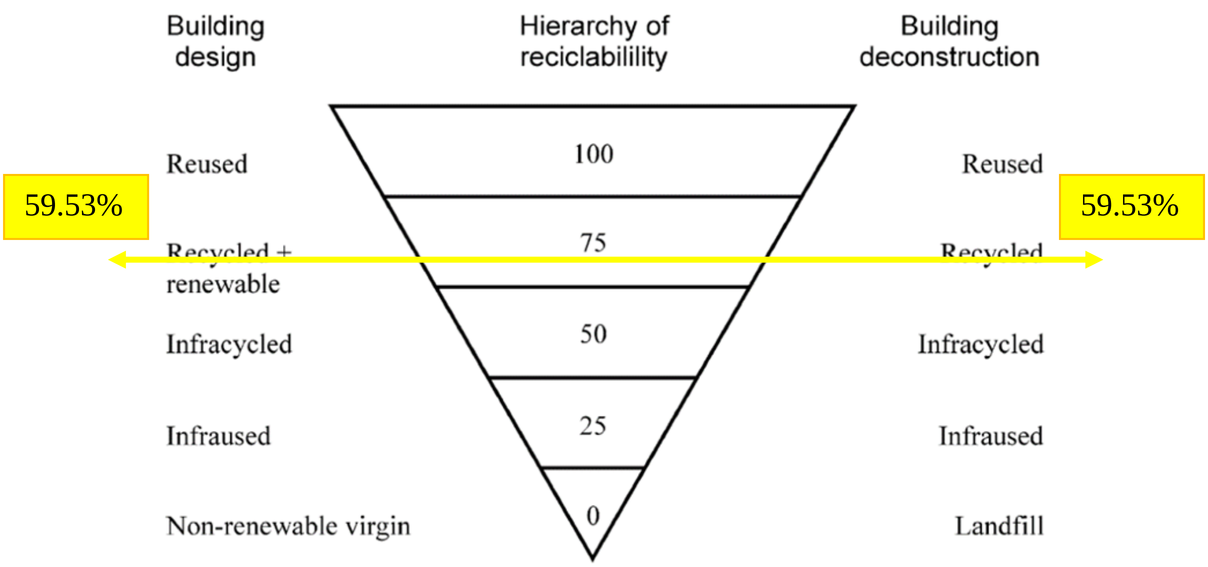

Figure 36 Classification of the structure

Table 10 presents indicator 2 and 3 under design optimization. Indicator 2 is the CO_2 emissions for the materials and the whole structure. Indicator 3 shows the amount of recyclable materials used by Multiconsult to design the building.

Table 10 Application of Indicator 2 and 3 in the Case Study

Design Optimization						
Materials		Weight (kg)	Density (kg/m3)	Emission Factor (kgCO2/kg)	CO2 emissions (kg)	Use of recyclable materials (kg)
1	Steel	155,800.30	7,860	1.55	241,490.46	0
2	Reinforced Concrete	1,562,363	2,400	0.0520	81,242.87	0
3	Prefabricated Concrete	1,981,858.70	2,400	0.1311	259,821.67	0
4	Rockwool	19,704.10	22	0.8152	16,062.78	0
5	Timber	494.30	800	0.49	242.21	0
Total		3,720,220.40			598,860.01	0.00

Column 1 shows the materials of the building. Column 2 shows the total weight of these materials. The total weight of the structure is presented at the bottom of column 2. The total weight for each material was easily calculated using BIM. It highlights the importance of a software that contains the information of the materials used in the structure.

Column 3 presents the density of the materials as additional information in case it is necessary for further calculations. The density can also be utilized to obtain the weight of the components by multiplying it by the volume. Column 4 shows the emission factor (kgCO2/kg) for each material. The emission factor was obtained from the Inventory of Carbon and Energy (ICE) free international database. As seen in column 4, the material with the highest emission factor is steel.

Column 5 shows the CO_2 emissions for the materials as well as the total CO_2 emissions of the building. The material with the highest CO_2 emissions in the project is the prefabricated beams used in the slab. As we can infer from the total CO_2 emissions of the project, the reuse of these materials will generate a tremendous positive impact for the environment since this building is only one of the many buildings a city has. The CO_2 emissions should be considered in the selection of materials. Ideally, a consulting company will choose materials with low CO_2 emission factor. Column 6 shows the total weight of recycled materials used in the design of the case study. This study assumes none of the components used in the building were reused or recycled from previous projects. That means all the structural components for the design and construction of the junior high school will use virgin materials.

Table 11 shows the application of the three indicators under the Design for Disassembly and Adaptation category. Indicator 4 is demountable connection, indicator 5 is accessible connection and indicator 6 is disassembly time.

Table 11 Application of Indicator 4, 5, and 6 in the Case Study

Design for Disassembly and Adaptation			
Connection	Demountable connection	Accessible Connection	Disassembly Time
1	No	Yes	-
2	No	Yes	-
3	No	Yes	-

This study has selected three connections to exemplify how the three indicators can be applied and how to analyze the connections of the building. Ideally, all the connections of the building must be analyzed and evaluated by these three indicators. Figure 37, 38 and 39 show the connections selected. Figure 37 shows an exterior connection of the concrete slab on the third floor. The elements in this connection are two steel columns, one steel beam (principal beam), two prefabricated concrete beams, and the concrete floor over the prefabricated concrete beams.

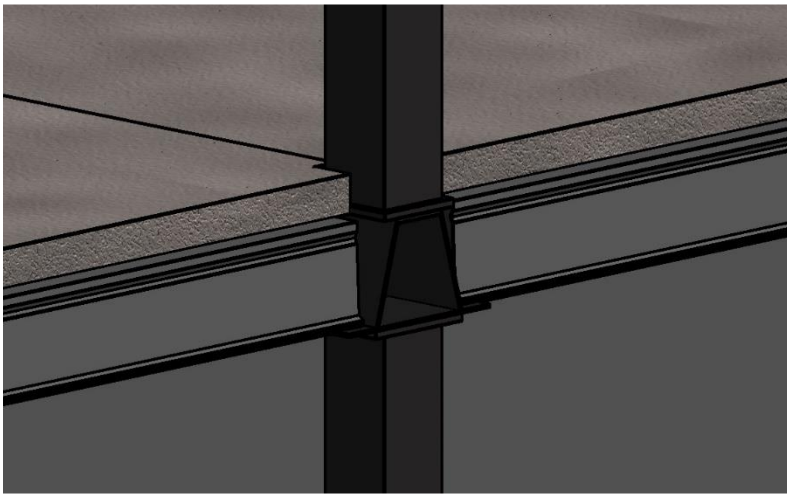

Figure 37 Connection 1

This study does not classify Connection 1 as a demountable connection. This study considers a demountable connection as a connection were all the elements can be recovered for further reuse in another project. For the disassembly of this type of connection, the layer of concrete floor must be demolished. The rest of the elements will most probably be damaged in this process.

Connection 1 is classified as an accessible connection. This is an exterior connection, so accessibility to the elements is easier than an interior connection. An interior connection also has more elements. The disassembly time of this connection is not applicable for this study, but it should be calculated or estimated by future studies or by the construction company at the end of the building’s life cycle.

Figure 38 shows an exterior connection of the roof, which is level 4 of the main building. The elements in this connection are one steel column, one steel beam (principal beam), one prefabricated concrete beam, and the rockwool layer over the prefabricated concrete beam.

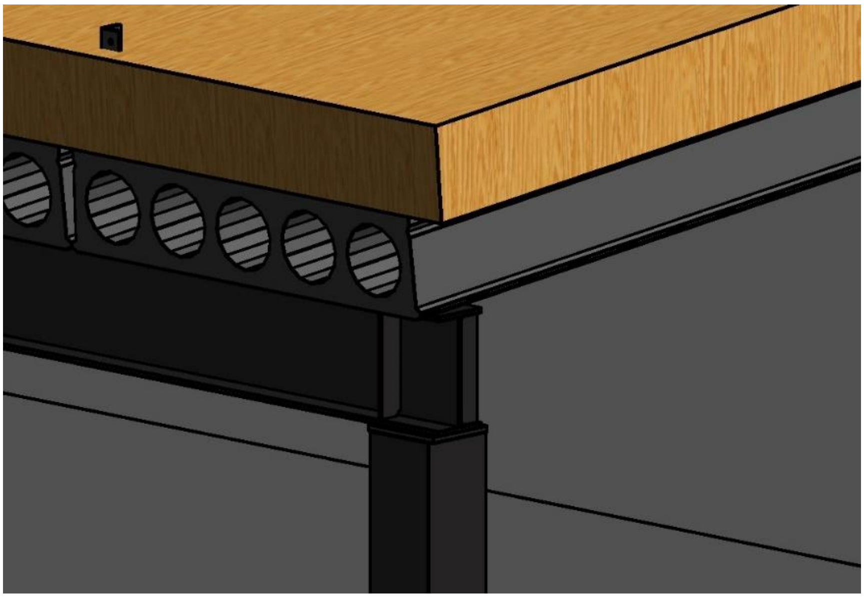

Figure 38 Connection 2

This study does not classify Connection 2 as a demountable connection. This study considers a demountable connection as a connection were all the elements can be recovered for further reuse in another project. The elements are joined by steel pins and angles. To remove the steel pins and angles the elements must be cut, tear down or demolished. The mechanical properties of the elements will be affected.

Like Connection 1, Connection 2 is classified as an accessible connection. This is an exterior connection, so accessibility to the elements is easier than an interior connection. An interior connection also has more elements. The disassembly time of this connection is not applicable for this study, but it should be calculated or estimated by future studies or by the construction company at the end of the building's life cycle.

Figure 39 shows an exterior connection of a steel beam and a steel column on the third floor of the building. The elements in this connection are two steel columns, one steel beam (secondary beam). On the other side of the column there is a steel plate connected. This connection is used to exemplify a steel to steel connection, and how it can be analyzed.

This study does not classify Connection 3 as a demountable connection. This study considers a demountable connection as a connection were all the elements can be recovered for further reuse in another project. This study assumes this steel to steel connection is welded. Whatever method selected by the construction workers to break the weld might damage the elements and affect their properties for further reuse.

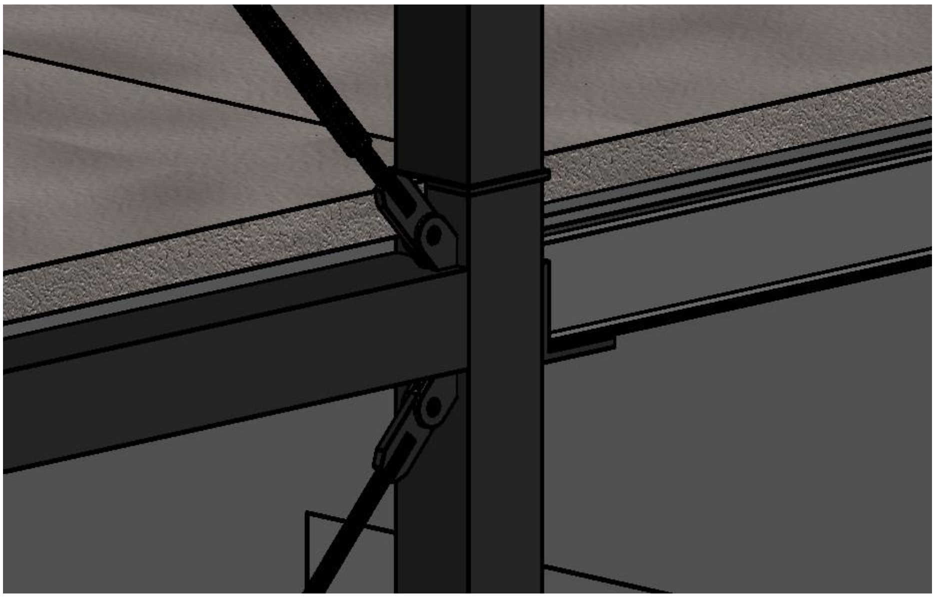

Figure 39 Connection 3

Like Connection 1 and 2, Connection 3 is classified as an accessible connection. This is an exterior connection so accessibility to the elements is easier than an interior connection. An interior connection also has more elements. The disassembly time of this connection is not applicable for this study, but it should be calculated or estimated by future studies or by the construction company at the end of the building's life cycle.

Table 12 shows the application of the last three indicators to the case study. These three indicators are under the End of Life Program category. Indicator 7 is materials used, indicator 8 is recycled materials and indicator 9 is the total weight of waste by type and disposal method.

Table 12 Application of Indicator 7, 8, and 9 in the Case Study

End of life Program				
Materials		Materials used (kg)	Recycled materials (kg)	Total weight of waste by type and disposal method (kg)
1	Steel	155,800.30	116,850.225	38,950.075
2	Reinforced Concrete	1,562,363	1,171,772.25	390,590.75
3	Prefabricated Concrete	1,981,858.70	1,486,394.025	495,464.675
4	Rockwool	19,704.10	14,778.075	4,926.025
5	Timber	494.30	370.725	123.575
Total		3,720,220.40	2,790,165.3	930,055.1

Column 1 shows the materials of the building. Column 2 shows the total weight of these materials and the total weight of the building at the bottom. Column 3 shows the materials that could be recycled from the case study after at the end of its life cycle. This study assumes that 75% of the materials will be recycled. The values in column 3 are the result of multiplying column 2 times 0.75. This percentage was obtained from the website of the US Environmental Protection Agency database in 2018.

Column 4 shows the total weight of waste that must be disposed to a landfill. The values in column 4 are the result of subtracting column 2 minus column 3. This total waste must be classified by type and disposal method. The main objective of integrating circular economy in the building design process is to eliminate this 25% of waste. Table 8 highlights the need and importance of a construction and demolition waste management plan for the construction companies since circularity has not been achieved yet.

4.6 Re-evaluation Analysis

A re-evaluation analysis of the structural components is necessary at the end of a project's life cycle to determine if the components are still in optimal conditions for further reuse in another projects. New materials, composites, and technologies are vital for the life extension of the products. It is also important to highlight that the evaluation methods do not have to damage or reduce in any form the mechanical properties of beams and columns. The following aspects must be evaluated:

- Strength
- Durability
- Defects
- Cracks
- Degradations
- Structural performance

The structural components of any construction project have a life span. If circular economy is to be fully applied in the construction industry, meaning future buildings will only use components and materials from older buildings, these buildings do not have to reach the limit of their design life. Otherwise the structural components will be obsolete. Non-structural products are easier to reuse since they do not support the different loads acting on the building. This re-evaluation is highly important since the majority and the most expensive products in a building are the beams, columns, plates, and trusses.

Current use and future use of the structural components must be considered. Every building has its own loads, material properties, geometry, and location. Ideally, construction companies will keep a good information database with the suggested Design Passport by this study to have a thorough understanding of all the materials and conditions of all the materials. Having a good information database and model can help the construction companies achieve a constant monitoring of the condition of the structure.

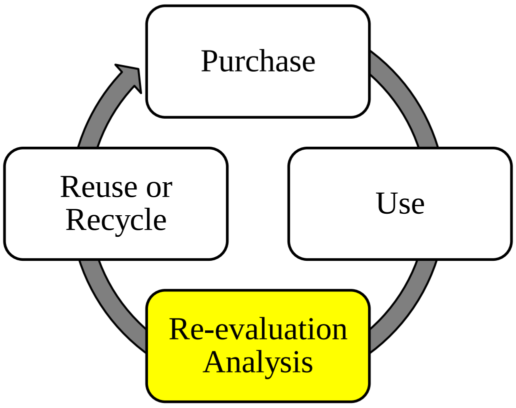

Figure 40 Waste chain management adapted from (SAR, 2021)

Figure 40 shows the waste chain management proposed by (SAR, 2021). SAR company is a global waste management partner and service provider. SAR emphasizes the concept of turning waste into value. As it is shown in Figure 40 the re-evaluation analysis is an important step to identify what products or materials can be reutilized in the system and what new products must be purchased. Companies want to ensure that their resources are kept in their life cycle as much as possible so that they keep generating profits without buying new resources.

The company also emphasizes the integration of different industries for the reduction of waste. This approach consists on having different industries or services working together so that what may be waste for a company in the construction industry it can be turned into value by another company in a different industry or vice versa. Companies like SAR can be hired by other companies so that SAR can manage the waste properly instead of doing it by themselves.

4.7 Design Passport

This section provides the relevant information a Design Passport must include to help a construction company implement, evaluate, and achieve circular economy in the building design process. A Design Passport must be unique for every project, since every project has its own characteristics, but this study suggests the information that is important and necessary for circular economy. The information for a Design Passport is presented and described as follows:

1. General information about the company and its employees.
2. Detailed information of the project and its location. Include relevant documents like the contract, blueprints, notes, tests results, material standards, and design codes.
3. A feasibility study as described in section 2.10 for the development and consideration of better materials and structural components for the project to have better reusability and recyclability.
4. A circular economy evaluation as presented in section 4.5 for the case study.
5. Re-evaluation analysis as explained in section 4.6.
6. Include a construction and demolition waste management plan.

4.8 Feasibility Study for the Case Study

This section presents the development of a feasibility study for the junior high school. The feasibility study will focus on different concept products for new and innovative structural components for the adaptation of circular economy. As mentioned in section 2.10 a feasibility study evaluates the factors which might affect a project. This study considers all the factors and constraints necessary for the development of the concept products for the junior high school. These concept products should consider reusability and recyclability as well as the specifications for the materials needed for this type of structure. Since the junior high school is already designed and built, this study also considers the existing components in the structure combining them with available materials in the market to achieve a better circularity.

The construction industry often ignores the manufacturing process of the structural components they design for the projects. As mentioned by this study, modular and industrial construction with prefabricated elements is necessary for the adaptation of circular economy. This study develops the following product development process for the junior high school. This product development process is adapted from Ulrich and Eppinger, (2016) and Luz et al. (2018).

1. Planning

Specify the function of the building, materials requirements, terrain conditions, budget, quality standards, and a schedule of completion.

2. Concept development

- Identify the needs of the market: adaptation of circular economy by developing reusable and recyclable products.
- Generate product concepts: description of the form, function, and features of the product.
- Define the specifications and costs of the product.

Products: the products are extracted from (Lindapter, 2021), a company developing innovative products to provide a faster, cost-effective alternative to on-site drilling or welding and are designed to reduce installation time and labor costs. Figure 41 shows the product for fixing the floor with the supporting beam and Figure 42 shows the CF clamp to hold together a metallic beam with a metallic column.

- Floor fixing Type 1055

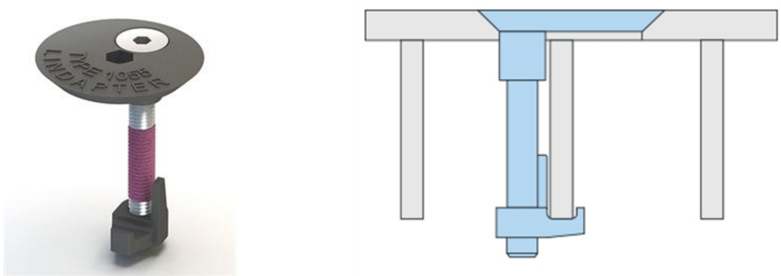

Figure 41 Floor fixing Type 1055 extracted from *(Lindapter, 2021)*

- Type CF High Slip Resistance Clamp

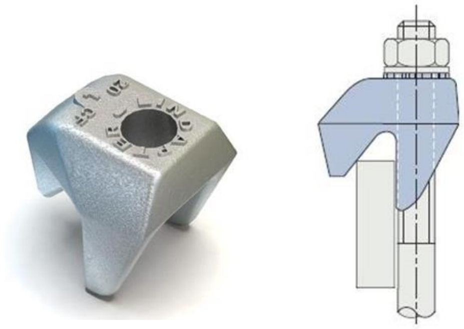

Figure 42 Type CF High Slip Resistance Clamp extracted from *(Lindapter, 2021)*

3. Design

In the design step of the process it is necessary to provide the specification of the geometry, materials, and requirements of all the unique parts in the product as well as blueprints or drawings of the product. Figure 43 shows the application of the floor fixing product and Figure 44 shows the application of the product in the slab of the case study. The floor fixing product provides a better alternative for disassembly instead of the steel bars that are seen in Figure 44.

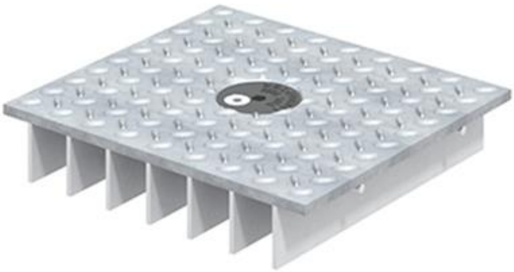

Figure 43 Application of the Floor Fixing extracted from *(Lindapter, 2021)*

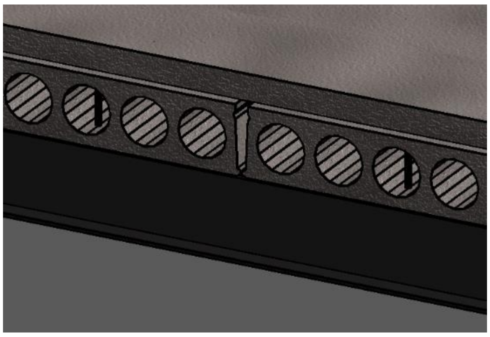

Figure 44 Application of the product in the case study

Figure 45 shows the application of the CF clamp to hold together a metallic beam with a metallic column and Figure 46 shows the application of the CF clamp in the case study. The CF clamp provides a better alternative for disassembly instead of welding together the metallic beam and column.

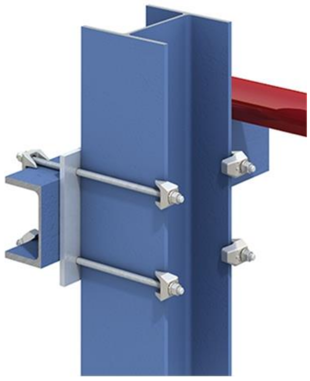

Figure 45 Application of CF Clamp extracted from *(Lindapter, 2021)*

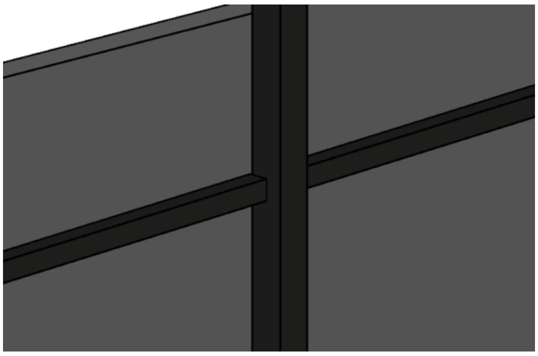

Figure 46 Application of CF Clamp in the case study

4. Testing

The structural analysis of the product must satisfy all the criteria according to the Eurocode. The structural elements must satisfy the Ultimate Limit State (ULS), Service Limit State (SLS), and the Seismic Load Case.

5. Fabrication

Define and adapt a final fabrication system: machines, workforce, and facilities needed to develop the product.

6. Review

Feedback from the stakeholders relevant to the design and construction of the project. The stakeholders for the case study "junior high school" are: architects, structural engineers, construction managers, and construction workers.

4.9 Analytical Hierarchy Model

The analytical hierarchy process (AHP) model assists the construction companies in the decision process of evaluating and determining if a structural element of the project can be reused or recycled. If the material is not reused or recycled it is considered as waste. This study selected as an example from the case study a precast reinforced concrete wall. This model can be applied to the elements the construction companies consider as relevant or applied to the whole project. The AHP model presented in Figure 47 utilizes the circular economy strategies and indicators presented in the literature review and implemented in the case study.

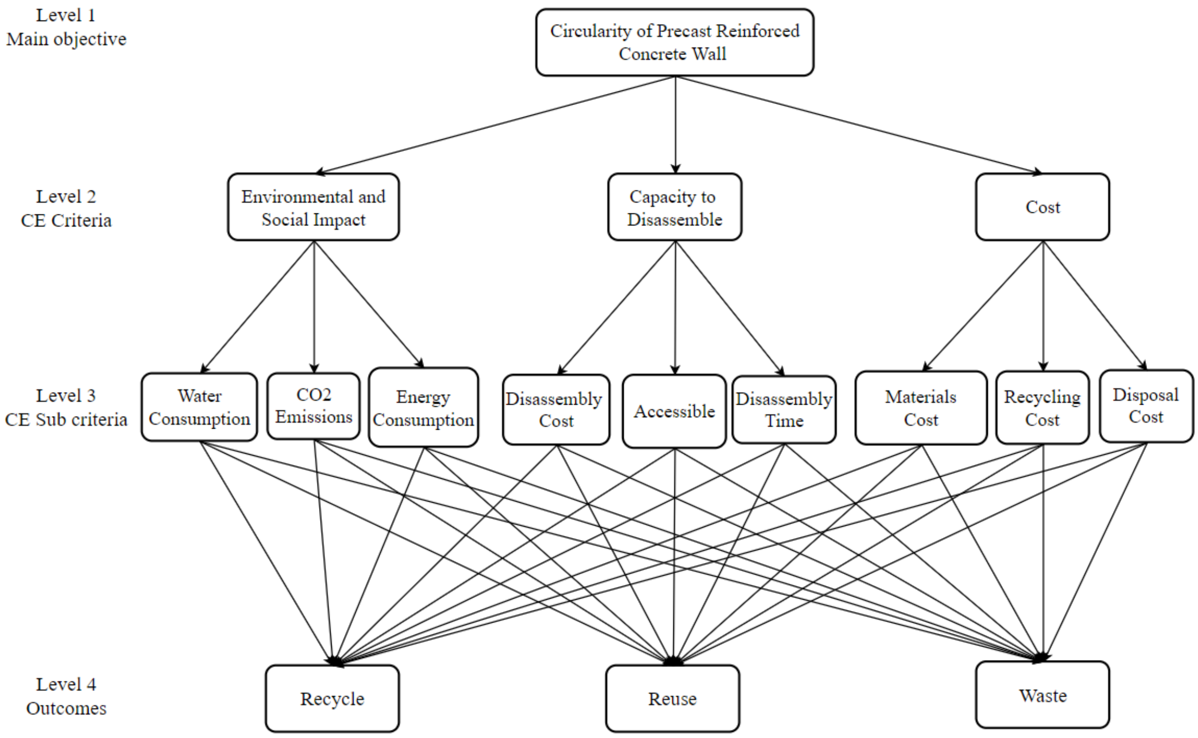

Figure 47 AHP model

The main objective of the decision hierarchy model is in Level 1. Level 2 consists of the circular economy criteria and Level 3 consists of the circular economy sub criteria or indicators to evaluate the circularity of the concrete element. Level 4 consists of the outcomes of the decision hierarchy model for the circularity of the precast reinforced concrete wall: the selected element can be recycled, reused, or considered as waste. Construction companies want to generate waste as little as possible so that their projects achieve circularity.

The software Expert Choice is used to evaluate the analytical hierarchy process. The software is used as decision support and provides a solution according to the importance of the criteria and sub criteria towards the main goal. The importance of the criteria and sub criteria towards the main goal is determined by the stakeholders of the project or experts in the field. The software also provides a feedback mechanism to analyze different what-if scenarios if the importance of the criteria or sub criteria is modified.

Table 13 shows the list and symbols of all the parameters used in the AHP model shown in Figure 47. All this information is important for analyzing the model in Expert Choice and establishing the comparison matrices.

Table 13 List of parameters from AHP model

Main Objective	G
Criteria	
Environmental and Social Impact	C1
Capacity to disassemble	C2
Cost	C3
Sub criteria	
Water consumption	S1
CO2 emissions	S2
Energy consumption	S3
Disassembly cost	S4
Accessible	S5
Disassembly time	S6
Materials cost	S7
Recycling cost	S8
Disposal cost	S9
Outcomes	
Recycle	O1
Reuse	O2
Waste	O3

Table 14 shows the matrix that is needed to determine the comparisons between the parameters. The table shows the matrix for the comparison between the criteria towards the main objective of the model. Viewing and analyzing the table from its left side, C1 is compared to the three columns (C1, C2, and C3), C2 is compared to the two columns (C2 and C3), and finally C3 is only compared to itself. The value “x” is the weight assigned in the evaluation to determine the importance between the two criteria. The value “1/x” is automatically determined by the software, which means the user does not have to consider this value in the evaluation. Figure 48 shows the evaluation of the criteria (Level 2) with respect to the main goal of the model (Level 1). Appendix B shows the comparison matrices of the lower levels of the model.

Table 14 Matrix of the comparisons between the main objective and the criteria

G	C1	C2	C3
C1	1	x	x
C2	1/x	1	x
C3	1/x	1/x	1

The evaluation or prioritization of all the parameters is carried out by applying the following values: Equal (1), Moderate (3), Strong (5), Very Strong (7), and Extreme (9). If the two parameters have the same importance with respect to the main goal, then a 1 is applied. If one of the parameters "Capacity to disassemble" is considered more important than the other one "Environmental and social impact" with respect to the main goal than the prioritization should be closer to number 9 on the side of the parameter "Capacity to disassemble". Appendix C shows all the evaluations of the lower levels of the model. The comparison and evaluation between the criteria and the sub criteria (Level 3) and the comparison and evaluation between the sub criteria and the three outcomes (Level 4). Each parameter of a certain level on the AHP model is analyzed with all the parameters in the level below

Which one is preferable with respect to the Circularity of Precast Reinforced Concrete Wall																		
Environmental and Social Impact	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Environmental and Social Impact
Environmental and Social Impact	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Capacity to disassemble
Environmental and Social Impact	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Cost
Capacity to disassemble	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Capacity to disassemble
Capacity to disassemble	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Cost
Cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Cost

Figure 48 Evaluation of the criteria with respect to the main goal

The main objective, criteria, sub criteria, outcomes, as well as all the comparisons and evaluations are input into the software to analyze the model. Figure 49 shows the main screen of the software and the results of the model beside each parameter. The criteria with a greater importance towards the main objective are "Capacity to dissemble". The three most important indicators in the sub criteria level are CO2 emissions, Accessible, and Recycling Cost. The outcome with more importance with respect to the goal is "reuse", followed by "recycle" and "waste".

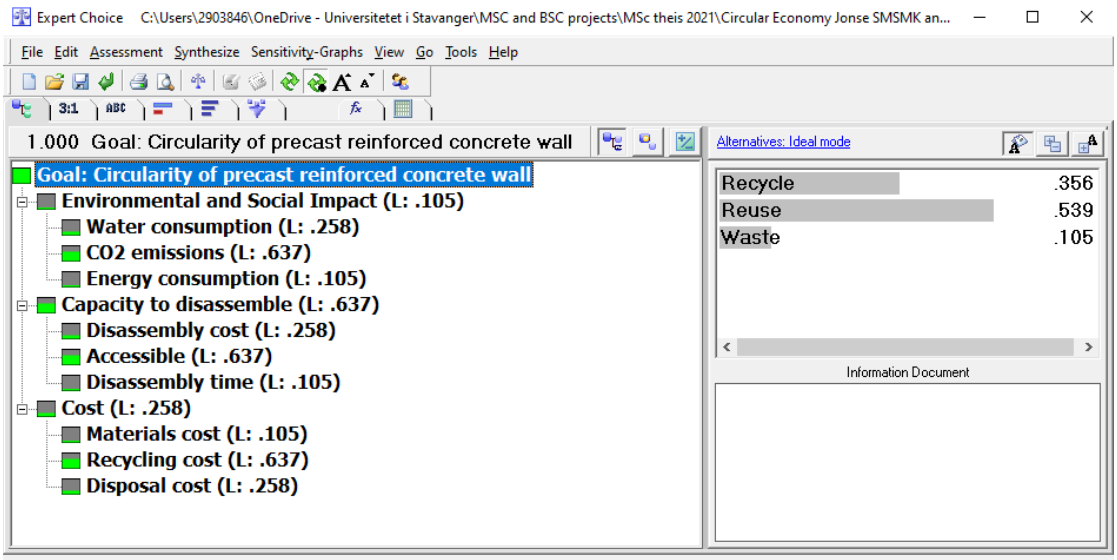

Figure 49 Expert choice software main screen

The outcomes emphasize what construction companies should aim when applying the circular economy strategies in their projects. By reusing the precast reinforced concrete wall, construction companies are avoiding the use and cost of new resources for a similar element in a future project. Additionally, the company is generating less waste from each project and protecting the environment. The second outcome is recycling the concrete element, which is also positive to the economy, environment, and society but the company is not receiving the same monetary value back for the element as highlighted by the recyclability indicator in section 4.5. The third outcome is waste and is the outcome construction companies do not want for their elements to achieve circularity in their projects. Figure 50 shows the ranking of the outcomes with respect to the main goal of the AHP model.

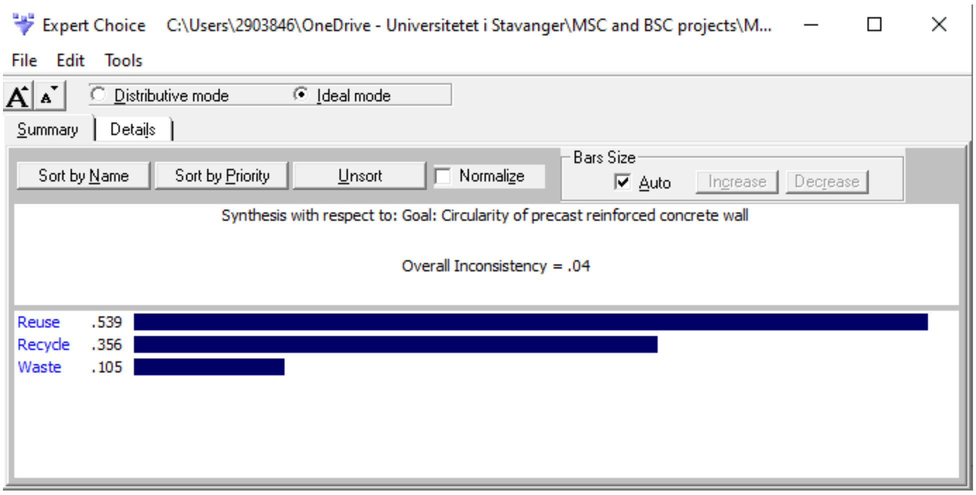

Figure 50 Importance of outcomes with respect to the main goal

Figure 51 shows the different types of dynamic graphs to perform the sensitivity analysis in the software. The sensitivity analysis allows the user to modify the evaluation of all the parameters to analyze the different scenarios that can result from these changes. Trying different scenarios can be important for construction companies to achieve the best selection.

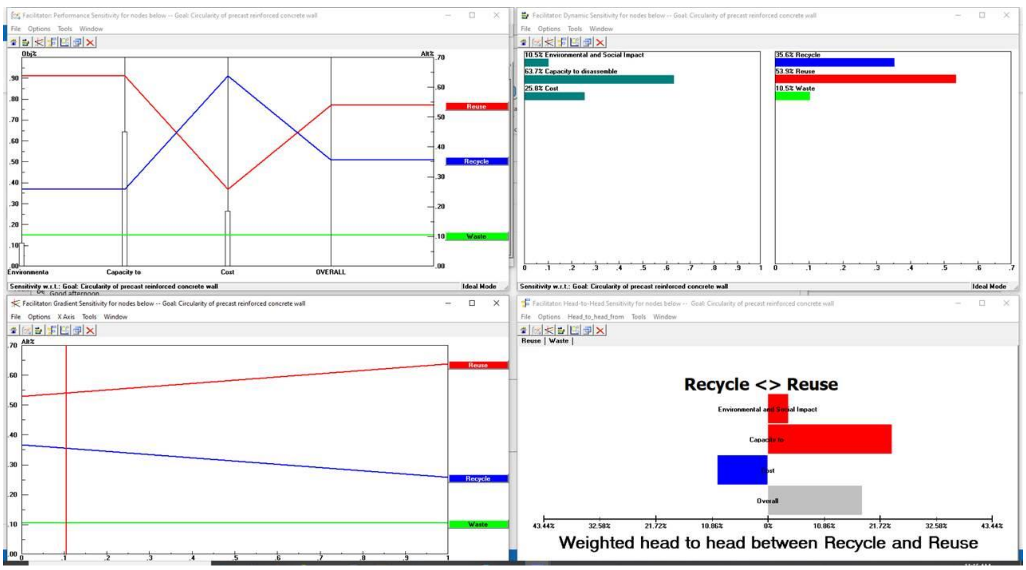

Figure 51 Sensitivity analysis of the AHP model

4.10 Circular Buildings Cases

This section describes the circular economy strategies or measures implemented by five buildings in the Netherlands (CFP Green Buildings, 2021). These circular building cases are presented to understand how to adapt circular economy strategies in the building design process. Circular buildings can be analyzed on further research to evaluate their circularity (reusability and recyclability) as well as their environmental performance.

1. The Green House – Utrecht

The building can be fully disassembled, and all materials are reusable. In addition, recycled materials were used as much as possible. And when the building is taken down, nothing will remain on or in the ground. The structure was built in such a way that there are no pipes, cables, or sewers in the ground. This will leave no residues on the ground after use. Figure 52 shows the green house in Utrecht.

Figure 52 The green house in Utrecht extracted from *(CFP Green Buildings, 2021)*

2. Temporary Courthouse – Amsterdam

The building is designed in such a way that it is easily disassembled and can also be given another function if necessary. To allow the building to be fully disassembled, a unique mounting system was developed for the hollow core slabs. This makes both the steel structure and the concrete floor slabs in the building fully reusable. Figure 53 shows the temporary courthouse in Amsterdam.

Figure 53 Temporary courthouse in Amsterdam extracted from *(CFP Green Buildings, 2021)*

3. Alliander Main Office – Duiven

Around 83% of the building is made up of recycled materials. The used wood comes from a waste processing company. All the scrap concrete from the old building was used as replacement gravel for new concrete. Most of the ceiling plates have been reused and the lamps are made from old transformers. They also used old materials for insulation. The insulation of the building is made of the old uniforms.

This building uses solar panels and groundwater for the ground source heat pump system, the office building is energy neutral. In addition, the roof collects rainwater. This water is used for the toilet facilities and for the watering of plants, among other things. It is the first building in the Netherlands with an energy positive construction site. The solar panels were deliberately installed earlier, so that the energy used in construction could be generated on-site. Figure 54 shows the Alliander main office in Duiven.

Figure 54 Alliander main office in Duiven extracted from *(CFP Green Buildings, 2021)*

4. Venlo Municipal Office

The building was designed and built following the cradle-to-cradle philosophy. All base materials used in the building can be fully reused without losing value. In addition, the office building is completely energy neutral with the use of solar panels, thermal energy storage, and solar boilers. Figure 55 shows the Venlo municipal offices.

Figure 55 Venlo municipal offices extracted from *(CFP Green Buildings, 2021)*

The production process and all materials used in the Venlo municipal office are not harmful to humans or the environment. The building provides a cleaner living environment due to the green walls with hundreds of plants that filter fine particles and nitrogen oxides out of the air. The air inside and around the building is demonstrably cleaner.

5. Circle Amsterdam

The building was finished in 2017 and is a popular meeting place in the Zuidas district in Amsterdam. Almost all materials used in the building are reused and can be disassembled. There are 500 solar panels on the roof that provide energy. Direct current is used instead of alternating current, keeping loss of energy to a minimum.

The window casings were used from old offices that were to be demolished, and the furniture was repaired and reused. Old jeans were converted into insulation material for the ceiling. Reuse of materials was not only considered during construction. During daily use of the building, circularity is also at the forefront. The employees' uniforms are made from old PET-bottles, and lectures are regularly held that focus on the circular economy. Figure 56 shows the Circle building in Amsterdam.

Figure 56 Circle Amsterdam extracted from *(CFP Green Buildings, 2021)*

Table 13 shows the circular economy strategies the five buildings in the Netherlands used to achieve circularity. Identifying and analyzing the strategies used by successful projects is important for construction companies to understand what strategies and measures they can implement to achieve circular economy. It is also important for future research to comprehend these strategies to develop new case studies or consulting interviews to the stakeholders of these projects who have achieved circularity.

This study highlights the fact that these five buildings are in the Netherlands. The location of the projects affects the results of the adoption of circular economy. The Netherlands is a country with great economy and advanced engineering. Developing case studies in other countries might present more challenges since they might not have the economic resources and technologies to implement the circular economy strategies mentioned in Table 15. The rules and regulations in the construction industry of the country might also affect the result of these strategies.

Table 15 Circular Buildings Strategies

Circular Buildings Strategies	
The Green House	1. Reusable materials 2. Recycled materials 3. Urban farm 4. No ground utilities
Temporary Courthouse	Unique mounting system for slabs
Alliander Main Office	1. Recycled materials 2. Reused materials 3. Solar panels 4. Groundwater 5. Rainwater collection
Venlo Municipal Office	1. Reusable materials 2. Solar panels 3. Thermal energy storage 4. Solar boilers 5. Green walls
Circle Amsterdam	1. Recycled materials 2. Reusable materials 3. Solar panels 4. Direct Current

5. DISCUSSION AND ANALYSIS

This section presents the discussion and analysis of this study. This section will analyze the results obtained from applying the concepts and strategies of circular economy to the junior high school building used as a case study. This section will also discuss about the current situation and the characteristics of the construction industry regarding the adoption of circular economy.

The construction industry has many different types of projects. The projects vary vastly in sizes, location, materials, and construction methods. This study used a junior high school building as a case study, but the design passport and feasibility study can be utilized in other different projects. This highlights the importance of carrying out case studies to have a better understanding how to adopt circular economy in different kinds of projects. Circular buildings are a relatively new concept construction companies want to implement. Few case studies have been done in the adoption of circular economy in the construction industry.

The design passport is a unique document for every project. Although the structural design aspects and indicators selected by this study can work for every project and company. Construction companies should devote time in analyzing their resources and procedures for a better adoption of circular economy. this study highlights the use of new materials and new technologies such a BIM software for an easier adoption of the circular economy. A well-developed Revit model facilitates the calculation of materials and their location.

The Revit model used by this study was not designed using the concepts and strategies of circular economy. Further research is needed to design or analyze structures that have been designed keeping in mind the adoption of circular economy. A comparison of these two types of buildings should be an interesting research to see if the circular economy strategies work and to what extent.

Doing research in the construction industry is complicated because the life span of a building is usually 50 years so having a complete case study from start to finish is impossible. Other projects such as bridges have an even longer life span of 100 years. Buildings that are designed adopting the concepts of circular economy could be analyzed in their different stages for a better understanding of the subject. Software simulations will play an important role for construction companies to analyze and understand how their projects will be constructed and disassembled at the end of their life cycle for a better reusability and recyclability.

The prices of the materials were calculated from a construction company in Honduras and the recycling prices were from different countries. Since the project is in Norway, using Norwegian construction prices and recycling prices will provide a more accurate result in the circular economy evaluation carried out in section 4.5. Additionally, this study selected representative elements and their reference prices for the circular economy evaluation. The ideal situation will be to use the accurate prices for all the structural elements in the Revit model. Multiconsult is a consulting company not a construction company and a construction company will probably not want to reveal the detailed costs of one of their projects.

6. CONCLUSIONS AND SUGGESTIONS

This study identified, defined, and described the concept, indicators, characteristics, and strategies of circular economy. Analyzed the implementation of circular economy in the construction industry and finally developed a BIM case study to show the implementation of circular economy in the building design process. This section presents the conclusions of this research and recommendations for further research on circular economy.

The five research methodologies used by the 30 journal papers analyzed by this study are: literature review, case study, experiment, survey, and delphi method. Most of the studies (14) selected a literature review to conduct their research. The application of a case study is the second most used research methodology, but it is only used 23% of the time (7 out of the 30 journal papers). The least used research methodologies are experiment (6), survey (2), and delphi method (1). Future research should develop more case studies or use different types of research methodologies, such as conducting interviews or applying questionnaires to different stakeholders in the construction industry to obtain new information and experiences of implementing circular economy strategies in construction projects.

The three structural design aspects categorized by this study are: design optimization, design for disassembly and adaptation, and end of life or program. These structural design aspects must be considered by construction companies for the adaptation of circular economy in the building design process. Three indicators were selected for each of the structural design aspects previously mentioned. These nine indicators will help the construction companies understand how to evaluate circular economy in the building design process of their own different projects. The nine indicators are: recyclability (%), CO2 emissions (kgCO2/kg), use of recyclable materials (kg), demountable connection, accessible connection, disassembly time, materials used (kg), recycled materials (kg), total weight of waste by type and disposal method (kg). The indicators were applied to junior high school in Bogafjell, Norway used as a case study for the evaluation of circular economy. The BIM model was provided by the Norwegian consulting company Multiconsult and consists only of the structural components of the project (footings, columns, beams, slabs, and roof).

A design passport is suggested by this study to help a construction company implement, evaluate, and achieve circular economy in the building design process. The design passport must be unique for every project, since every project has its own characteristics, but this study suggests the information that is important and necessary for circular economy. A re-evaluation analysis of the structural components is necessary at the end of a project's life cycle to determine if the components are still in optimal conditions for further reuse in another projects. The analytical hierarchy process assists the construction companies in the decision process of evaluating and determining if a structural element of the project can be reused or recycled. This study selected a precast reinforced concrete wall from the case study to apply the model. Additionally, a feasibility study is also suggested by this study to help construction companies have a better selection of their materials and better product development for the implementation of circular economy. The initial selection of the proper materials is highly important to achieve a better reusability or recyclability at the end of the life cycle of any building.

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APPENDIX A

Study	CE Indicators Proposed
Study 1 Kubbinga et al. (2018)	1. Possibilities of building refurbishment 2. Minimizing the square meters of development 3. Minimizing the total material mass 4. De/re-mountable connections 5. Accessible Connections 6. Local supply of reusable/secondhand materials. 7. Use of recyclable materials 8. Use of building material passport 9. Available building material passport 10. Demolition specifications 11. Disassembly guidelines 12. No materials from the C2C Banned List of Chemical Materials are used 13. Building products have no or minimal VOC (Volatile Organic Compounds) emissions
Study 2 Rincón-Moreno et al. (2021)	14. Self-sufficiency for raw materials 15. Percentage of CE procurement 16. Generation of waste per € (kg/€) 17. Percentage of generation of waste per material consumption 18. Energy productivity (kWh/€) 19. Percentage of green energy consumption 20. Water consumption productivity (m3/€) 21. Percentage of recycling rate of all waste 22. Percentage of recycling rate of plastic waste 23. Percentage of recycling rate of paper and paper board 24. Percentage of circular material use 25. Percentage of percentage of CE investment 26. Percentage of CE jobs 27. Percentage of CE patents
Study 3 Yadav et al. (2020)	28. Adoption of innovative practices 29. Advanced technological transfer and applicability 30. Penetrating social media and big data analytics within the organization 31. Effective facility layout decision making 32. Constant monitor on changing market needs 33. Effective information management system 34. Effective planning & management for CE adoption 35. Top management commitment for CE adoption 36. Allocation of financial budgets

Study 3 Yadav et al. (2020)	37. Sustainable resource management 38. Sustainable participation of stakeholders 39. Building brand image 40. Economic and social benefits of CE 41. Adopting industrial ecology initiatives 42. Availability of CE oriented framework 43. Redesign based on customer feedback 44. Effective life cycle analysis 45. Rewards and incentives for greener activities 46. Identifying performance measures for CE 47. Supportive government policies 48. Adoption of 6 R's 49. Employee empowerment and motivation 50. Multi-stage quality check system 51. Focused training for CE adoption 52. Effective inventory management 53. Reduction in carbon emission 54. Coordination and collaboration among SC members 55. Supplier commitment for recyclable materials 56. Adopting reverse supply chain practices 57. Adopting green practices 58. Educating customers for CE practices
Study 4 Moraga et al. (2019)	59. Self-sufficiency for raw materials 60. Green public procurement 61. Waste generation 62. Food waste 63. Recycling rates 64. Recycling / recovery for specific waste streams 65. Contribution of recycled materials to raw materials demand 66. Trade in recyclable raw materials 67. Private investments, jobs and gross value added 68. Patents related to recycling and secondary raw materials
Study 5 De Pascale et al. (2020)	69. Disassembly Effort Index 70. Circular Economy Toolkit 71. End-of-Life Index 72. Recycling Indicator Set 73. Reuse Potential Indicator 74. CE Index 75. Material Circularity Indicator 76. Recyclability Benefit Rate 77. Eco-cost Value Ratio 78. CE Indicator Prototype 79. Synthetic Economic Environmental Indicator

Study 5 De Pascale et al. (2020)	80. Longevity Indicator 81. Material Reutilization Score 82. Recycling Index 83. Circular Economy Performance Indicator 84. Product-level Circularity Metric 85. Value-based Resource Efficiency Indicator 86. End-of-life Indices 87. Recycling Desirability Index 88. Sustainable Circular Index 89. Global Resource Indicator 90. Circularity Design Guidelines 91. Combination Matrix 92. Effective Disassembly Time 93. Ease of Disassembly Metric 94. End-of-use Product Value Recovery 95. Circularity Calculator
Study 6 Padilla-Rivera et al. (2021)	96. Decent work and economic growth 97. Responsible consumption and production 98. Good health and well-being 99. No poverty 100. Zero hunger 101. Peace, justice, and strong institutions 102. Reduced inequities

APPENDIX B

C1	S1	S2	S3
S1	1	x	x
S2	1/x	1	x
S3	1/x	1/x	1

S4	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

C2	S4	S5	S6
S4	1	x	x
S5	1/x	1	x
S6	1/x	1/x	1

S5	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

C3	S7	S8	S9
S7	1	x	x
S8	1/x	1	x
S9	1/x	1/x	1

S6	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S1	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S7	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S2	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S8	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S3	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

S9	O1	O2	O3
O1	1	x	x
O2	1/x	1	x
O3	1/x	1/x	1

APPENDIX C

Which one is preferable with respect to Environmental and Social Impact																		
Water consumption	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Water consumption
Water consumption	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CO2 emissions
Water consumption	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Energy consumption
CO2 emissions	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	CO2 emissions
CO2 emissions	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Energy consumption
Energy consumption	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Energy consumption

Which one is preferable with respect to Environmental and Social Impact																		
Water consumption	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Water consumption
Water consumption	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	CO2 emissions
Water consumption	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Energy consumption
CO2 emissions	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	CO2 emissions
CO2 emissions	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Energy consumption
Energy consumption	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Energy consumption

Which one is preferable with respect to Capacity to Disassemble																		
Disassembly cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Disassembly cost
Disassembly cost	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Accessible
Disassembly cost	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Disassembly time
Accessible	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Accessible
Accessible	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Disassembly time
Disassembly time	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Disassembly time

Which one is preferable with respect to Cost																		
Materials cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Materials cost
Materials cost	9	8	7	6	5	4	3	2	1	2	3	4	**5**	6	7	8	9	Recycling cost
Materials cost	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Disposal cost
Recycling cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycling cost
Recycling cost	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Disposal cost
Disposal cost	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Disposal cost

Which one is preferable with respect to Water Consumption																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to CO2 Emissions																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Energy Consumption																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Disassembly Cost																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Accessible																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Disassembly time																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	**3**	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Materials Cost																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Recycling Cost																		
Recycle	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	**1**	2	3	4	5	6	7	8	9	Waste

Which one is preferable with respect to Disposal Cost																		
Recycle	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Recycle
Recycle	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reuse
Recycle	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Reuse	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reuse
Reuse	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Waste
Waste	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Waste