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Architecture for Sustainable Design

MASTER THESIS

LIFE CYCLE ASSESSMENT (LCA) IN BUILDINGS

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ABSTRACT

Climate change is an evident fact of our age. The building and construction industry has a great responsibility for energy use, waste generation, and CO2 emissions. The concept of the circular economy (CE) arose in the 1970s with the goal of minimizing the use of inputs for industrial production, but it has been shown to be theoretically applicable to any resource. Circular economy suggests a shift in the "extraction-production-disposal" linear economy (LE) paradigm, which is now in use on a broad scale in the industry. On the contrary, the circular economy promotes a design and building methodology which is recyclable, reusable, and more durable. In order to reduce the buildings' environmental impacts, the transition towards a circular economy in the building sector is vital in order to build more sustainable communities. Many tools have been used to assess the environmental impacts of the buildings. Life cycle assessment or LCA is the most widely used methodology amongst them for assessing environmental impacts associated with all the stages of the life cycle of a product or a system. This study aims to assess the environmental impacts of the office building based on three end-of-life scenarios by using the Life Cycle Assessment methodology. Different scenarios compare business-as-usual and circular building life cycles. Scenario 1, represents the business-as-usual building life cycle which is demolished and landfilled after the service life, as the second scenario includes an end-of-life scenario with material recycling. The third and final scenario represents circular economy principles adopted in the building. In such a manner, building components are reusable after the service life. The aforementioned life cycle scenarios were modeled in OpenLCA software and environmental impacts were calculated in 5 impact categories: global warming potential, acidification, smog formation potential, ozone depletion potential, and eutrophication potential. Life Cycle Impact Assessment results have shown that Scenario 1 with the business-as-usual system boundary has the highest impact on every impact category. Whereas the second scenario has a less environmental impact and the third scenario with circularity principles has the lowest environmental impact due to the reuse of the components. This study concluded that extending the life cycle of the building components through reuse or recycling could reduce the total environmental impact of the building. Since our built environment is based on the linear economy nowadays, the transition to circular buildings can reduce our energy consumption and waste generation. The building industry has the potential to reduce its environmental impacts by adopting circular economy principles.

Keywords: Life Cycle Assessment (LCA), Circularity

INDEX

List of Abbreviations

LCA-Life Cycle Assessment

LCI- Life Cycle Inventory

LCIA- Life Cycle Impact Assessment

CE-Circular Economy

LE-Linear Economy

ISO-International Standards Organization

EoL-End of Life

C&DW-Construction and Demolition Waste

CO_2 - Carbon Dioxide

EU- European Union

GHG-Green House Gas

ISO- International Organization for Standardization

EPD- Environmental Product Declarations

DfD-Design for Disassembly

BaU-Business as Usual

GWP-Global Warming Potential

ODP-Ozone Depletion Potential

POCP-Smog Formation Potential

ELCD-European reference Life Cycle Database

EF-Environmental Footprint

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CHAPTER 1: INTRODUCTION

1.1. Background

Although the concept of sustainable development is gaining popularity, many business executives are unfamiliar with it. The concept remains abstract and theoretical for the majority of people. Sustainable development needs to be integrated into business enterprises in order to achieve its potentials. (International Institute for Sustainable Development, 1992)

The building and construction sector is responsible for a tremendous amount of energy use and greenhouse emissions. During the construction and operation stages, buildings demand a vast amount of energy and result in excessive use of natural resources. Every year, the construction industry consumes more than 400m tonnes of materials only in the UK, becoming the country's greatest consumer. (Arup, 2016)

In 2017, the construction and operation of buildings accounted for 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions. (International Energy Agency and the United Nations Environment Programme, 2018). Another environmental burden derived from the construction and building sector is waste. In the European Union (EU), the construction sector is responsible for 35% of total waste generation in comparison with other economic sectors. According to the data from 2014, 850 million tonnes of waste were generated in the EU, by construction and demolition activities. (Eurostat, 2018)

As a result of non-OECD countries' fast urbanisation, the construction industry is expected to consume 21% of global energy and 32% of operational energy for buildings by 2040. By 2050, approximately 60% of the total planned infrastructure must be built, depleting Earth's resources exponentially. (United Nations Environment Programme, 2012)

The term circular economy (CE) first arose in the 1970s to reduce natural resource usage for industrial products. (Stahel, W. 2016) CE proposes a change in the traditional paradigm of the linear economy “extraction-production-disposal’’. (Ellen McArthur Foundation, 2013). CE aims to reduce the environmental impacts of industries by closing the loops in production.

Under a part of the Paris Agreement, the international community agreed to keep global average temperatures no more than 2 ℃ over pre-industrial levels and to work to keep them no more than 1.5 degrees ℃ above pre-industrial levels. Following the agreement, the building sector drew attention to reducing greenhouse gases (GHG) derived from building-related activities. Since buildings have a severe impact on the environment, to build a sustainable society, it is vital to apply circular economy principles in the building industry.

Upon growing awareness of environmental issues, several tools are developed to assess the sustainability of buildings from different perspectives. (Buyle,Braet,&Audenaert, 2013) Among those methodologies, Life Cycle Assessment is the most accepted scientific methodology for perceptible assessment of building related environmental impacts over the whole lifespan. (Lotteau, Loubet, Pousse et al, 2015)

Life Cycle Assessment is a ‘’cradle to grave’’ method that addresses the environmental impacts of a product, or a system throughout its life cycle. (ISO 14040, 2006) "Life cycle" the term usually refers to the key actions that occur during the life of a product, from its manufacturing, usage, and maintenance to its final disposal, including the purchase of raw materials necessary to create the product. (SAIC, 2007) Life Cycle Assessment method is useful to comprehend the impacts derived on buildings in various categories: human health, the natural environment, and natural resources.

During the transition to a sustainable society, Life Cycle Assessment plays a big role in the future design of buildings and urban environments since it promotes the adaptation of the circular economy principles. This is due to the fact that circularity helps to provide economic growth without damaging global ecosystems. (Goldstein, B., & Rasmussen, F. N. , 2017) The application of the life cycle approach to buildings is fundamental to understanding the environmental burden. LCA is a method that allows architects and building-related professionals to assess and evaluate energy use and environmental impact deriving from the building life cycle. (Material extraction, construction, operation, and end of life) (The American Institute of Architects, 2010) LCA allows architects and building-related professionals to prioritise the optimization efforts based on evidence and to evaluate specific processes in the context of the building's overall life cycle. European standards for sustainable construction also adopted LCA to the Construction Products Regulation and several certification systems for sustainable buildings. (Danish Transport and Construction Agency, 2016)

1.2. Problem Statement

People use the equivalent of 1.6 Earths to meet their daily resource needs and absorb the waste which follows. As a result of this measurement, the Earth now takes one year and six months to replenish what humans use in a year. If current trends continue, humanity will require the equivalent of two planets by 2030, according to calculations. (W.E. Rees, Ref. Mod. in Life Sci. 24, 2017)

Turning resources into waste faster than they can be replenished causes ecological overshoot, an unsustainable situation that we must all solve. Toxins are accumulating in the atmosphere, water, and on ground as a result of the linear use of natural resources and the treatment of outputs as waste. The extraction, usage, and disposal processes have hastened the depletion of resources. (Vigovskaya, Aleksandrova,Bulgakov, 2018)

The current linear economy is built on a model that begins with raw material extraction and continues to produce with customer disposal after use, allowing billions of tons of raw materials to enter the industrial chain. The linear economy principle prioritizes social benefits over environmental implications, eventually leading to resource depletion. The linear 'take-make-dispose' model relies on large quantities of easily accessible resources and energy, and as such is increasingly unfit for the reality in which it operates. Working towards efficiency alone (a reduction of resources and fossil energy consumed per unit of manufacturing output) will not alter the finite nature of their stocks but can only delay the inevitable. A change in the entire operating system is necessary. (Towards to Circular Economy, 2013)

Construction and demolition waste (C&DW) is among the major waste streams generated in the EU, accounting for roughly 25% to 30% of all garbage generated in the EU and containing a variety of recyclable resources. As seen in Figure 1, there are significant differences across the EU-28 Member States in terms of waste generation and the activities which contributed to waste formation. Nonetheless, C&DW is responsible for a significant portion of waste generation in the majority of countries. (European Commission, 2018)

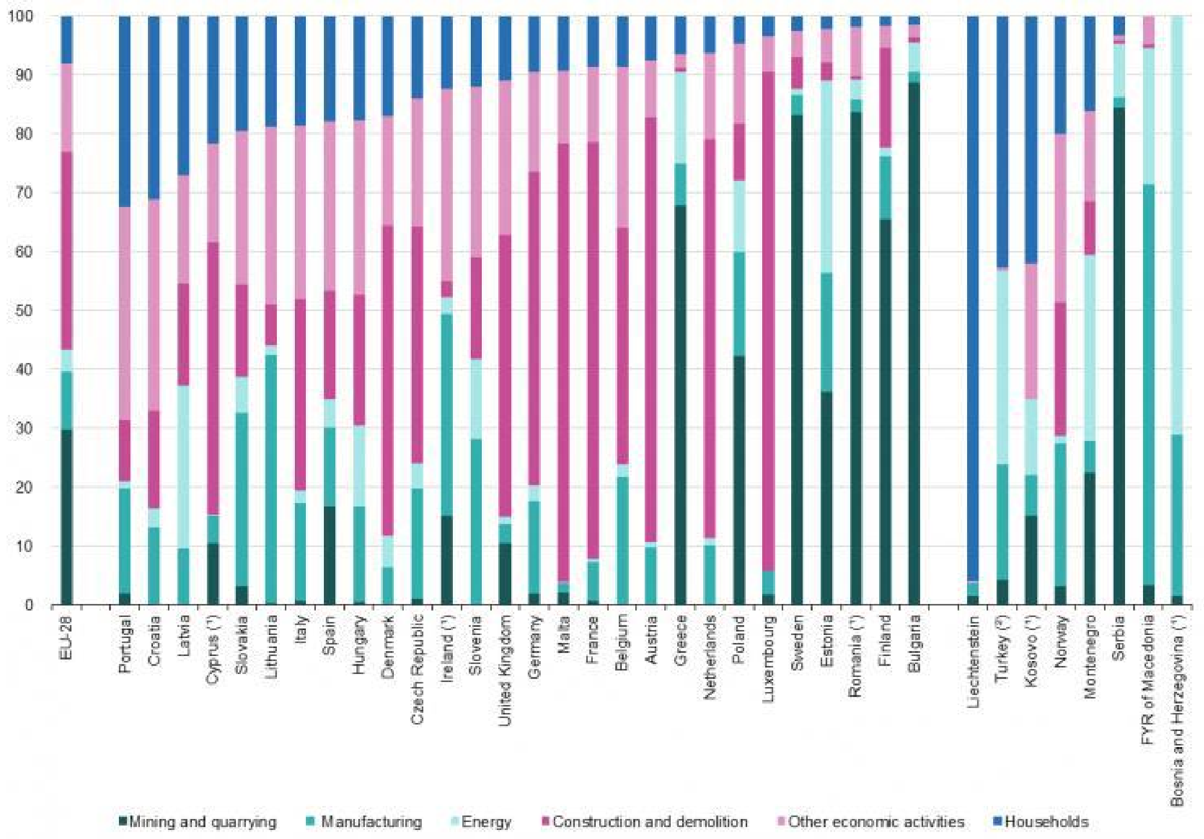

Figure 1: Waste generation by economic activities and households, EU-28, 2014 (European Commission, 2018)

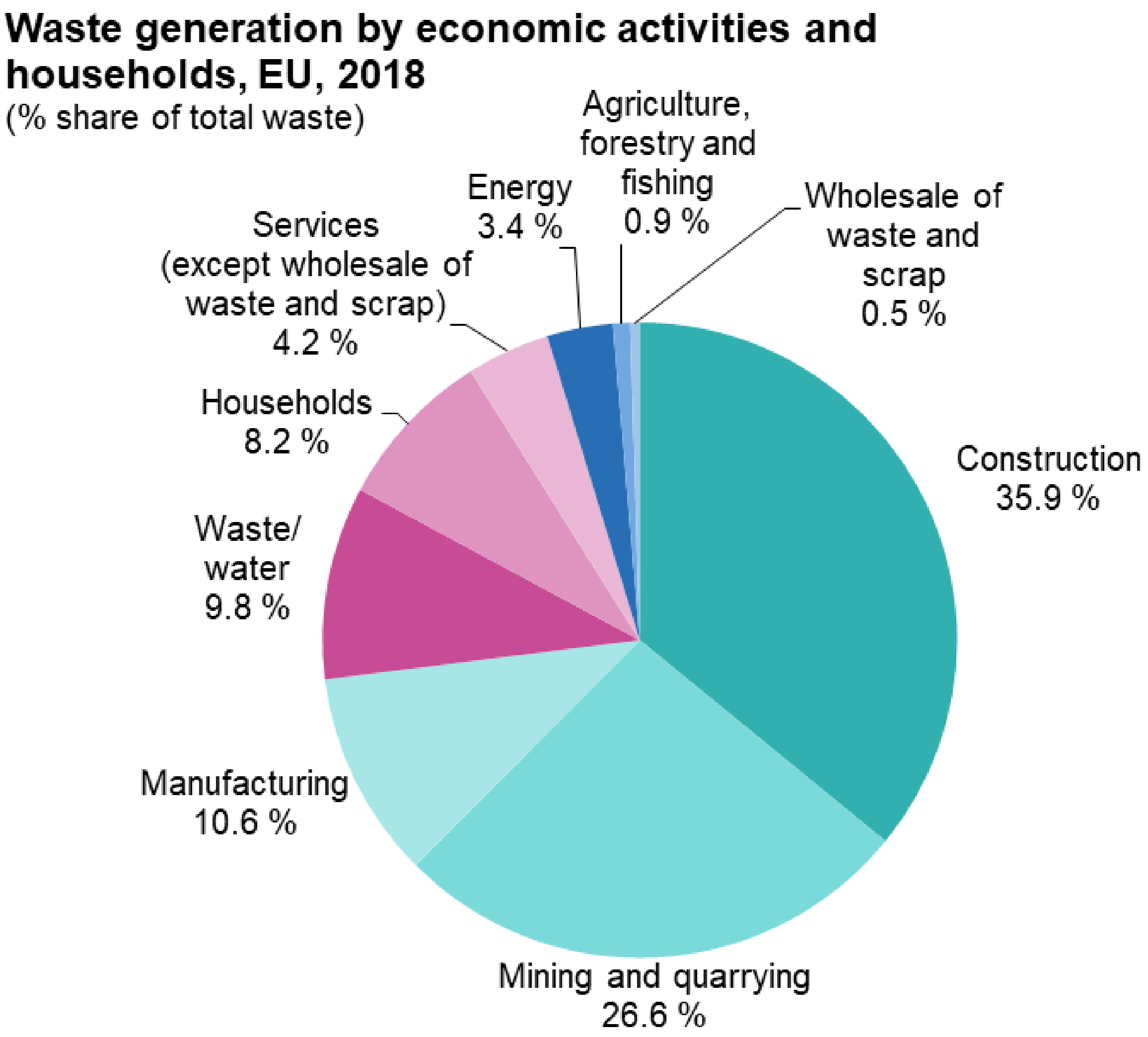

Figure 2: Waste generation by economic activities and households, EU, 2018 (Eurostat, 2018)

According to UNEP's Sustainable Buildings and Climate Initiative, buildings account for 40% of the solid waste streams in developed countries (UNEP, 2012)

Recent trends in energy consumption and emissions from the global buildings and construction sector are variable, with increasing energy use but little growth in emissions. Buildings accounted for 36% of global final energy use and 39% of energy-related CO2 emissions in 2017. The buildings and construction sector has a large share of energy and emissions, even excluding construction-related energy used for transport (associated with moving building materials to and from construction sites).

Taking into consideration all the data presented above, it is evident that taking an action against climate change is a principal responsibility of every business sector. Architects and building professionals, as an active actors in the building and construction sector, are responsible of reducing the waste generated from construction and demolition activities and limiting the emissions of CO2. Business-as-usual practices in the industry resulted in the generation of waste, resource depletion, and excessive energy use. There hasn't been a significant attempt the shift to more sustainable strategies in the building sector. As we live on a planet with limited resources, it is necessary to intervene in the current business practices. Therefore, this study is going to focus on the environmental impacts of the buildings more specifically the waste generation by the end-of-life scenarios. Current linear economy principles contribute the waste generation and energy use. Implementations of circular strategies in the building sector are going to be addressed and results will be compared.

1.3. Objectives

The primary objective of this thesis is to analyse the selected case study building to quantify environmental impacts during its complete life cycle by applying the life cycle assessment method based on 3 different end-of-life scenarios. To assess and compare environmental impacts, three end-of-life scenarios were implied in the case study building. Scenarios represent the business-as-usual practices and the adaptation of circular principles in the building design. The desired outcome of the study is to assess whether circular design principles will affect the total impact or not. The service life of the building is considered 50 years. Operational phase activities such as total energy use, water use, and waste generation are also included in the total calculations.

Life cycle scenarios are assessed in this study as follows:

Scenario 1- Material Extraction-Construction-Operation-Demolition and landfilled

Scenario II- Material Extraction-Construction-Operation-Recycling of materials

Scenario III-Material Extraction-Construction-Operation-Reuse of components

As Scenario I represents the current business-as-usual life cycle of the building, once the building completes its service life, it is demolished and the waste is landfilled. Scenario II implies the material recycling process at the end of service life. Therefore, after the completion of the service life, the building is still being demolished but the materials like wood, glass, and concrete are recycled. In scenario III, the most circular scenario, the building parts (structure, slabs, window frames, etc.) are designed to be circular. Therefore, after the completion of the life cycle, the building components can be reused in different buildings. In this way, components are expanding their life cycle and emissions derived from the initial raw material extraction and manufacturing of the parts are avoided.

1.4. Research Questions

Life cycle assessment is one of the finest methods for enabling architects and other building professionals to comprehend energy usage and other environmental impacts associated with all phases of a building's life cycle. The total environmental impact of a building depends on the building’s design, materials that were used, and finally end-of-life treatments. This study aims to address the following questions through the implementation of the Life Cycle Assessment method in an administration building in Germany, designed by UNStudio. Three end-of-life scenarios are created to compare and assess the impact of variation on business-as-usual and circular practices. This study aims to address the following questions:

-How do different end-of-life scenarios affect the total environmental impact caused by the building?

-Does circular economy principles adopted in building design reduce the total environmental impact of a building?

In answering those questions above, the study helps in providing a better sustainability assessment of an office building. Although the use of the Life Cycle Assessment approach in the construction industry is relatively new, past research has often concentrated on particular elements of the building. In this study, the aim is to address the whole building's environmental impacts by using the Life Cycle Assessment methodology. The following chapter will explore the circular economy, life cycle concept, and the standards of Life Cycle Assessment but also present the implementation of the life cycle methodology in the building industry.

1.5. Thesis Structure

This thesis is composed of five chapters in which the methodology of Life Cycle Assessment is analysed and then implemented on the case study project.

In particular, the first chapter provides a background of current problems in the building industry due to the disadvantages of the linear economy model. Following, the use of Life Cycle Assessment and beneficial points are addressed.

The following Literature Review chapter gives detailed information regarding the concept of circular economy, the life cycle concept, the concept of building life cycle, and finally addresses the ISO Standards of the LCA methodology. Later on, studies where LCA has been implemented in the building sector, are presented.

The third chapter of the thesis is dedicated to describing the methodological framework of this study. In the third chapter, the goal and scope of this study, system boundaries, and functional unit is explained. Besides, detailed data regarding the case study building is presented in the Life Cycle Inventory subchapter.

Furthermore, in the fourth chapter life cycle scenarios are explained and then the results of this each scenario are presented in detail. A comparison of the results also takes place in this chapter.

Finally, the fifth and last chapter draws a conclusion to this study where key findings, limitations, and future developments are demonstrated.

The structure of the thesis is summarized and illustrated in the scheme with the division into five chapters. (Figure 3)

LCA of BUILDINGS THESIS STRUCTURE

CHAPTER 1	The chapter is dedicated to providing background information and state the current problems in the building industry. Objectives of the study, problems, and research questions are demonstrated.
CHAPTER 2	The Literature Review chapter illustrates the necessary ISO Standards of LCA, the circular economy concept, and the life cycle of a building. Later on, case studies where LCA is applied in the building sector are presented.
CHAPTER 3	The chapter illustrates the methodological framework of this study. Goal and scope, system boundaries, functional unit, and other mandatory LCA input were addressed.
CHAPTER 4	Chapter four includes the detailed demonstration of 3 life cycle scenarios that were used on the LCA calculations,results of the LCA are also presented in this chapter.
CHAPTER 5	The final chapter discusses and interprets the results of the life cycle analysis. Key findings, limitations of the study, and future developments were represented in this chapter.

Figure 3: Schematic summary of thesis chapters

CHAPTER 2: LITERATURE REVIEW

This chapter presents the current literature addressing the research topic of this study, the life cycle assessment of buildings. Before going into detail about the life cycle analysis of buildings, it is useful to understand the concept of the life cycle and the life cycle assessment methodology. Moreover, it is necessary to understand the circular economy model, which is the starting point of the life cycle concept. Therefore, in the following subchapters, the circular economy model is explained, ISO standards were established to conduct a Life Cycle Assessment and four mandatory stages of LCA are demonstrated. The indicators of the LCA results and so-called impact categories are explained. Thereafter, since this study is focused on the Life Cycle Assessment of a building, the stages of the building life cycle are illustrated. The related chapter depicts the life cycle stages of a building. Subsequently, previous research papers on Life Cycle Assessment are investigated and some examples are presented. The literature review chapters conclude with the definition of circular building design strategies.

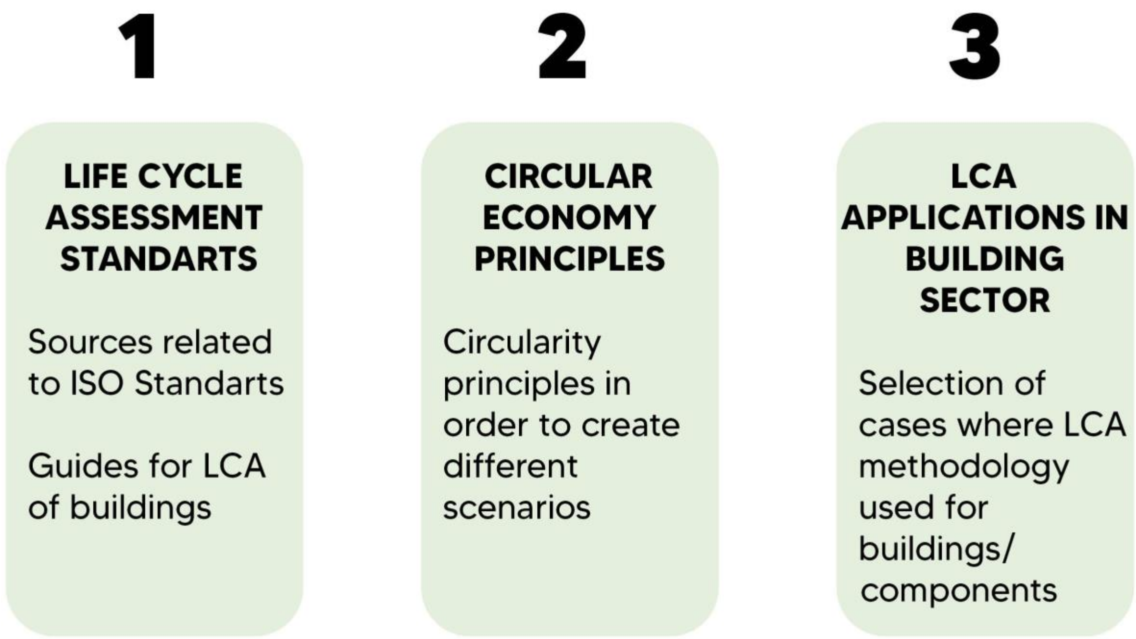

Figure 4: Literature Review framework

2.1. Circular Economy

Circular Economy (CE) emerged in the 1970s intending to reduce input consumption for industrial production, but it has proven to be potentially applicable to any commodity. CE proposes a change in the "extraction-production-disposal" paradigm of the linear economy (LE), which is currently applied on a large scale in the industrial environment by using the natural cycle model to make the human activity more resilient.

The main principle of circular economy (CE) is the concept of “cradle-to-cradle” in generation and utilization through the application of reuse of components, recuperation, and reusing of materials and energy.

The linear 'take-make-dispose' model is progressively unsuitable for the reality in which it operates because it relies on large amounts of easily accessible resources and energy. Working toward efficiency alone—reducing the number of resources and fossil energy consumed per unit of manufactured output—will not change the finite nature of their stocks, but will only postpone the inevitable. A complete operating system replacement appears to be required.

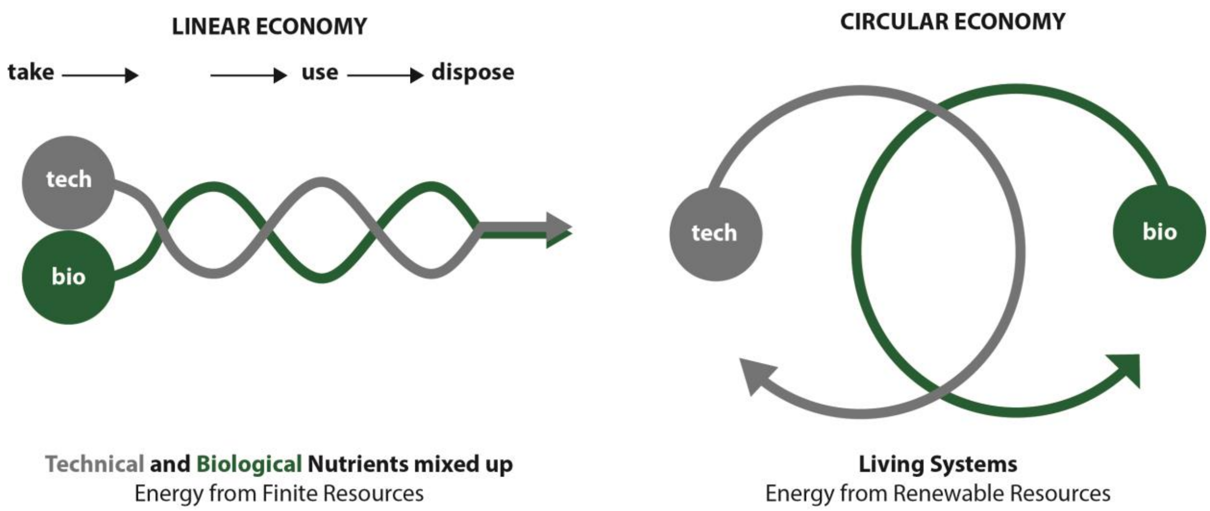

Figure 5: Circular and Linear Economy (Adopted from Ellen McArthur Foundation)

CE is based on the following principles: the design of manufactured products with added value and highest use in longer life cycles; the development of versatile products with different uses at different stages of their useful life, thereby ensuring the reuse of a single good; a systematic approach to supply chain management that evaluates the interconnections between the energy produced, the extracted material, and the natural environment, as well as a systemic approach to supply chain management that evaluates the interconnections between the energy produced, the extracted material, and the natural environment

The circular economy approach gives a chance to undertake the necessary step change. It intends to detach growth in the economy from the consumption of resources. Instead, products and assets are designed and constructed to be more durable, as well as repairable, refurbished, re-useable, and disassembled. This keeps components and their materials as useful as possible for as long as possible, reducing resource waste. By shifting away from the linear model and toward an ecosystem that preserves and enhances natural capital, renewable resources are optimized, waste is avoided, and negative externalities are designed out. Instead, materials, products, and components are held in loops that keep them at their highest intrinsic value.

From a circular economy point of view, design for deconstruction or design for disassembly is important so that buildings are designed to maximise the reuse and recycling of valuable materials and components during the disassembly stage.

However, the circular economy aims not only to preserve the value of products at the end-of-life stage but also to preserve the value of products in the economy for as long as possible. As a result, design for adaptability, which allows buildings to perform their functions for a longer period of time, and design for durability, which encourages the use of materials with long service life and fewer maintenance requirements, are design strategies that allow complying with the above requirement.

2.2. Embodied Energy

The overall energy necessary in the formation of a building, including direct energy utilized in the construction and assembly process, and indirect energy required to create the structure's materials and components, is characterised as embodied energy. This indirect energy will include all energy required from raw material extraction, processing, and manufacturing, as well as all energy used in transportation during this process and the relevant portions of the energy embodied in the infrastructure of factories and machinery of manufacturing, construction, and maintenance.

2.3. Life Cycle Concept

According to ISO14040 Standards (2006), the life cycle is described as "Stages that follow one another and are interconnected within a product system, from the acquisition or generation of raw materials from natural resources to final disposal."

The term "life cycle" also describes the key processes that take place during the duration of a product's lifetime, including the acquisition of the raw materials needed to make the product as well as its usage, maintenance, and disposal.

Every process or product goes through different stages or phases throughout its life. Each stage consists of a variety of activities. These phases can be roughly categorized as material acquisition, production, usage and maintenance, and end-of-life for industrial items. Buildings fall under the more precisely defined categories of manufacturing materials, construction, usage and maintenance, and end of life.

The start of the life cycle is also known as the "cradle," the "gate" is the point at which the manufacturing facilities exit and the "grave" is the point at which the life cycle ends. As a result, phrases like "cradle-to-grave" and "cradle-to-gate" are used to describe various stages of the life cycle. (The Carbon Leadership Forum, 2019)

2.4. Life Cycle Assessment

Life cycle assessment is a “cradle-to-grave” method for evaluating the environmental burdens of products or systems. "Cradle-to-grave" refers to the process that starts with the collection of earth's natural resources to make a product and concludes with the return of all resources to the planet. LCA assesses every stage of a product's life from the viewpoint that they are interrelated, which means that one action triggers another. LCA makes it possible to calculate the overall environmental effects of all phases of the product life cycle, frequently taking into account effects that are not taken into account in more conventional studies (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). LCA offers a full perspective of the environmental characteristics of the product or process and a more thorough understanding by taking into account the consequences throughout the product life cycle.

LCA is a technique that helps architects and other building-related professionals understand the energy usage and other environmental implications of all stages of a building's life cycle: material production, construction, operation, and decommissioning. (The American Institute of Architects, 2010)

For the majority of technological sectors, the International Organization for Standardization (ISO) has established international standards. More than 350 international standards were released by the ISO during the 1980s and 1990s when environmental issues began to be dealt with considerable care. The ISO 14040 to ISO 14049 series of standards are mostly related to LCA, with ISO 14040 and ISO 14044 being particularly well-known to LCA practitioners as fundamental standards.

The first standard, ISO 14040:2006, offers fundamental guidelines and a framework for LCA. It covers goal and scope definition, a description of the phases of life cycle inventory analysis and impact assessment, critical review, limitations, connections between the phases, requirements for using value choices, and optional elements without specific LCA techniques or methodologies for each phase.

In order to more closely resemble the structure of ISO 14040:2006, ISO 14044:2006 has replaced ISO 14041, 14042, and 14043. The following standard, ISO 14046:2014, provides information on an LCA framework for determining the water footprint of any organization, process, or product.

It offers precise instructions on how to evaluate and submit a water footprint analysis, either as a stand-alone assessment or as a component of a thorough evaluation. Life cycle impact assessment (LCIA) is described in ISO 14044:2006, while ISO14047:2012 gives examples of how to carry out the LCIA phase. ISO 14048:2002 has offered guidelines for data documentation, allowing LCA practitioners to interchange LCA and LCI data for uniform data documentation and document transparent data. LCA standards by ISO are listed chronologically in Table 1.

Standard Number	Standard Title
ISO 14040:2006	Environmental management—Life cycle assessment—Principles and framework
ISO 14044:2006	Environmental management—Life cycle assessment—Requirements and guidelines
ISO 14046:2014	Environmental management—Water footprint—Principles, requirements, and guidelines
ISO 14047:2012	Environmental management—Life cycle assessment—Illustrative examples of application of ISO 14044 to impact assessments
ISO 14048:2002	Environmental management—Life cycle assessment—Data documentation format
ISO 14049	Environmental Management—Life cycle assessment—Examples of application of ISO 14041 to goal and scope definition and inventory analysis

Table 1: ISO Standards for LCA throughout the years

The definition given by ISO14040 for Life Cycle Assessment is ‘’Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle’’ (ISO14040, 2006)

As demonstrated in Figure 6 below, Life Cycle Assessment has 4 stages:

1) Goal and scope definition

2) Inventory analysis,

3) Impact assessment

4) Interpretation. (ISO, 2006)

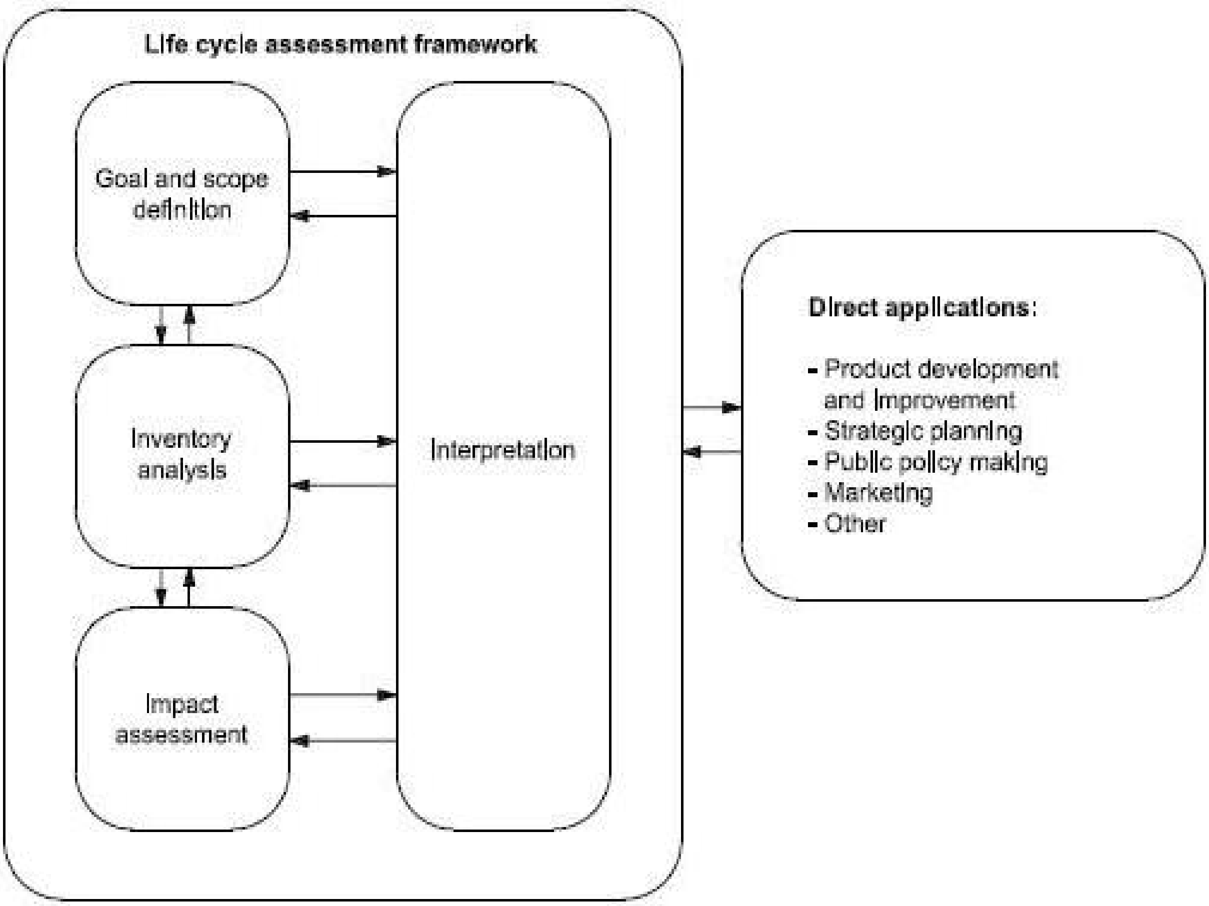

Figure 6: Stages of LCA (ISO14040, 2006)

Life cycle assessment is a ‘’cradle to grave’’ method that analyses industrial systems. The cradle-to-grave approach of the raw materials to the point where all the materials complete their life and go back to nature. Thanks to LCA, the environmental impacts derived from all the stages could be estimated. In this way, LCA provides a clear view of the underlying environmental trade-offs when choosing products and processes. (SAIC, 2006)

The European Commission concluded in its Communication on Integrated Product Policy that Life Cycle Assessment is the best currently available methodology for assessing the possible environmental implications of products. LCA is a frequently used tool for assessing the environmental implications of all phases of a building's life cycle. LCA can be used to assess structures on a variety of levels, including building materials and products, building sections and elements, entire buildings, and even entire neighborhoods. LCA is used in building certification schemes (such as BREEAM) and environmental labels (such as Environmental Product Declarations (EPD)) to quantify, communicate, and manage environmental consequences from the entire building or individual building components. (European Parliament, 2003)

Product Stage			Construction Stage		Use Stage							End-Of-Life Stage				Benefits And Loads Beyond The System Boundary		
Raw Material Supply	Transport	Manufacturing	Transport to the Site	Installation	Use/Application	Maintenance	Repair	Replacement	Refurbishment	Opeerational Energy Use	Operational Water Use	Demolition/Deconstruction	Transport	Waste Processing	Disposal	Reuse	Recovery	Recycling
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3

Figure 7: Life cycle stages according to EN standard

2.5. Goal and Scope Definition

This stage involves defining the product(s) or service(s) to be evaluated, selecting a functional unit, and specifying the needed level of detail. The sort of analysis, impact categories that must be assessed, and data collection requirements are identified. System boundary and the definition of functional units are essential components of this stage. The functional unit is a very detailed description of the system or product being evaluated so that the resulting LCA may be directly compared to the LCA of a similar system or product. The definition of the functional unit is a key LCA element. As the basis for LCA calculations, the functional unit is a quantitative evaluation of the function that a good or service delivers. A functional unit's principal aim is to supply a point of reference for the inputs and outputs. The main aim purpose of conducting an LCA is usually to comprehend the building's environmental impact, however, there are possibilities of defining specific goals:

-Assistance with design choices

-Declaration of performance of building regard to the legal codes

-Reporting the environmental performance

-Support the regulation development (The Carbon Leadership Forum, 2019)

Product systems are used in LCA to characterize the essential components of physical systems. The unit processes that must be a part of the system are specified by the system boundary. The inputs and outputs at the product system's border should ideally be represented as simple flows. The quantification of such inputs and outputs, though, need not be done if it does not materially alter the study's overall findings.

When setting the system boundary, several life cycle stages, unit processes, and flows should be taken into consideration, for example, the following:

– acquisition of raw materials;

– inputs and outputs in the main manufacturing/processing sequence;

– distribution/transportation;

– production and use of fuels, electricity, and heat;

– use and maintenance of products;

– disposal of process wastes and products;

– recovery of used products (including reuse, recycling, and energy recovery);

– manufacture of ancillary materials;

– manufacture, maintenance, and decommissioning of capital equipment;

– additional operations, such as lighting and heating. (ISO14040)

2.6. Life Cycle Inventory Analysis (LCIA)

Inventory analysis deals with the data collection and calculation procedures to quantify relevant inputs and outputs of a product or a system. It is the stage where the energy and raw materials used and the emissions to the atmosphere, water, and soil are quantified for each step in the process. The impact assessment may also include the process of re-evaluating the goal and scope of the LCA study with the aim of determining whether the objectives of the study have been met or not. If necessary modify the goal and scope if the assessment indicates that they cannot be achieved.

2.7. Impact Assessment

Impact assessment converts emissions from a particular product or process into impacts on a variety of human and terrestrial ecosystems. To make the impact more understandable, the impact of resource use and generated emissions can be grouped, quantified in a limited number of categories, and weighted in terms of importance. In other words, the inventory analysis data (phase 2) comes from the correct effect category identified in scoping (phase 1). The results of this step can be obtained for different classes of effects. Alternatively, you can get a single-value result by applying weights. The impact assessment stage can be analysed through life cycle indicators.

2.8. Interpretation

The results of life cycle assessments are reported in the most useful way and systematically assess the need and possibility of reducing the impact of a product or service on the environment. The results of this step are directly useful when making environmentally friendly decisions. LCA can be an iterative process. Therefore, the LCA interpretation can lead to proposed design changes, which can lead to step 2 of the process.

3. IMPACT CATEGORIES

The total derived emissions from the processes are categorized into different groups which are called environmental impact categories. In order to calculate the potential environmental impact, all the inputs and outputs related to the system are considered. In order to evaluate the results of LCA, a range of indicators may be used. According to the ISO14040, 2006 impact categories can be grouped as their subject of impact.

1. Resource Use
2. Ecological Consequences
3. Human Health

The most used impact categories in the LCA studies are listed as follows.

3.1. Global Warming Potential

Global warming potential is the increase of the surface temperature on a local, regional or global scale, caused by the high concentration of greenhouse gases in the atmosphere. Global Warming Potential is very much correlated with the other 2 impact categories -acidification and smog formation- since one of the main reasons for global warming is burning fossil fuels which also contributes to the other two impact categories.

3.2. Acidification Potential

Acidification happens when carbon dioxide dissolves in water or soil, on this occasion, the PH level decreases and water becomes more acidic. This impact category indicates the substances with potential acidifying effects on soil and water. In LCA, this category focuses on local effects.

3.3. Eutrophication Potential

Indicates the event of certain species dominating the ecosystem and jeopardizing other species' survival conditions. The addition of nutrients in the soil and sea causes this event. As an example, fish perish by depleted water oxygen caused by the excessive growth of algae. (Life Cycle Assessment of Buildings: A Practice Guide, 2019)

3.4. Ozone Depletion Potential

Indicates a decrease in the ability of the ozone layer to block ultraviolet radiation from the sun to the Earth's surface. Building materials do not affect the ozone layer on a concerning level but refrigerants used in machines are has a significant effect.

3.5. Smog Formation Potential

Indicates the formation of photochemical smog due to the presence of substances like carbon monoxide and volatile organic compounds (VOCs) in the atmosphere. Smog has a significant amount of ritofor human health and for the ecosystem that causes respiratory problems.

3.6. Abiotic Depletion Potential for Non-fossil Resources

Represents the excessive use of abiotic resources and as a result the depletion of current elements or depletion of metals and minerals.

3.7. Abiotic Depletion Potential for Fossil Resources

Focused on the high use of abiotic resources which may contribute to the deficiency of vacant fossil energy sources like oil or coal.

3.8. Total Use of Primary Energy

This category addresses danger in the case of the high use of resources from renewable and non-renewable sources can strengthen the depletion of natural resources.

3.9. Use of Renewable Secondary Fuels

This category deals with secondary fuels such as waste. In principle, secondary fuels are limited resources as well. Therefore, excessive use of secondary fuels would also lead to a scarcity of resources. Life Cycle Assessment impact categories with their abbreviation and related units are listed in Table 2.

IMPACT CATEGORY	ABBREVIATION	UNIT
Global Warming Potential	**GWP**	CO2 equivalents
Ozone Depletion Potential	**ODP**	R11 equivalents
Smog Formation Potential	**POCP**	Ethylene equivalents
Acidification Potential	**AP**	SO2 equivalents
Eutrophication Potential	**EP**	PO4 equivalents
Abiotic Depletion Potential for Non-fossil Resources	**ADPe**	Sb equivalents
Abiotic Depletion Potential for Fossil Resources	**ADPf**	MJ
Total Use of Primary Energy	**(PEtot)**	MJ or kWh
Use of Renewable Secondary Fuels	**(Sec)**	MJ or kWh

Table 2: Impact Categories and units

4. Building Life Cycle

Life Cycle Assessment is a method that is used to quantify the environmental impacts of products and systems. It is originally developed to assess industrial small-scale products. Nowadays, LCA is used to analyze buildings or building components to provide guidance in the decision-making processes. From the cradle-to-grave perspective, it is possible to list the life cycle stages of a building as well as a simple product. Typical life cycle stages of a building are defined as; production and construction, use or operation, end of life, and externalized impacts beyond the system boundary. (The Carbon Leadership Forum, 2019)

Environmental impacts from buildings are often generated from energy consumption during the use phase. (e.g. heating, lighting). According to estimates, the usage phase in conventional buildings accounts for around 8% to 90% of total lifetime energy consumption, with material extraction and manufacturing accounting for 10% to 20% and end-of-life treatments accounting for less than 1%. (Kotaji, Schuurmans, Edwards S, 2003)

A building's life cycle can be illustrated in 5 stages;

1. Product Stage: This stage deals with the products are materials used in the building. Raw material extraction to manufacture the materials, manufacturing processes, and transportation processes are included in this stage.

2. Construction process stage: This stage involves all the activities regarding the construction of the building. The journey of the construction products from the construction line to the place where they are going to be installed is taken into the consideration. As well as the transportation of the materials.

3. Use stage: This stage involves the operation of the buildings. The energy used for heating, cooling, and lighting included as well as the maintenance and refurbishment of the materials are included. The processes in this stage are summed up for the total years of the service life of the building and are often based on scenarios ad predictions.

4. End-of-life stage: In this step, the processes after the completion the life cycle of the building are handled. This stage is usually also based on estimations. Activities following after the demolition of the building such as recycling and landfilling are taken into consideration and included in the LCA calculations.

5. Benefits and loads beyond the system boundary: The calculated benefits and downsides of reusing and recycling building products/materials are included in this scenario-based step. According to EU standards, this stage must be reported separately and contributions from this stage should be considered outside of system boundaries. (Danish Transport and Construction Agency, 2016)

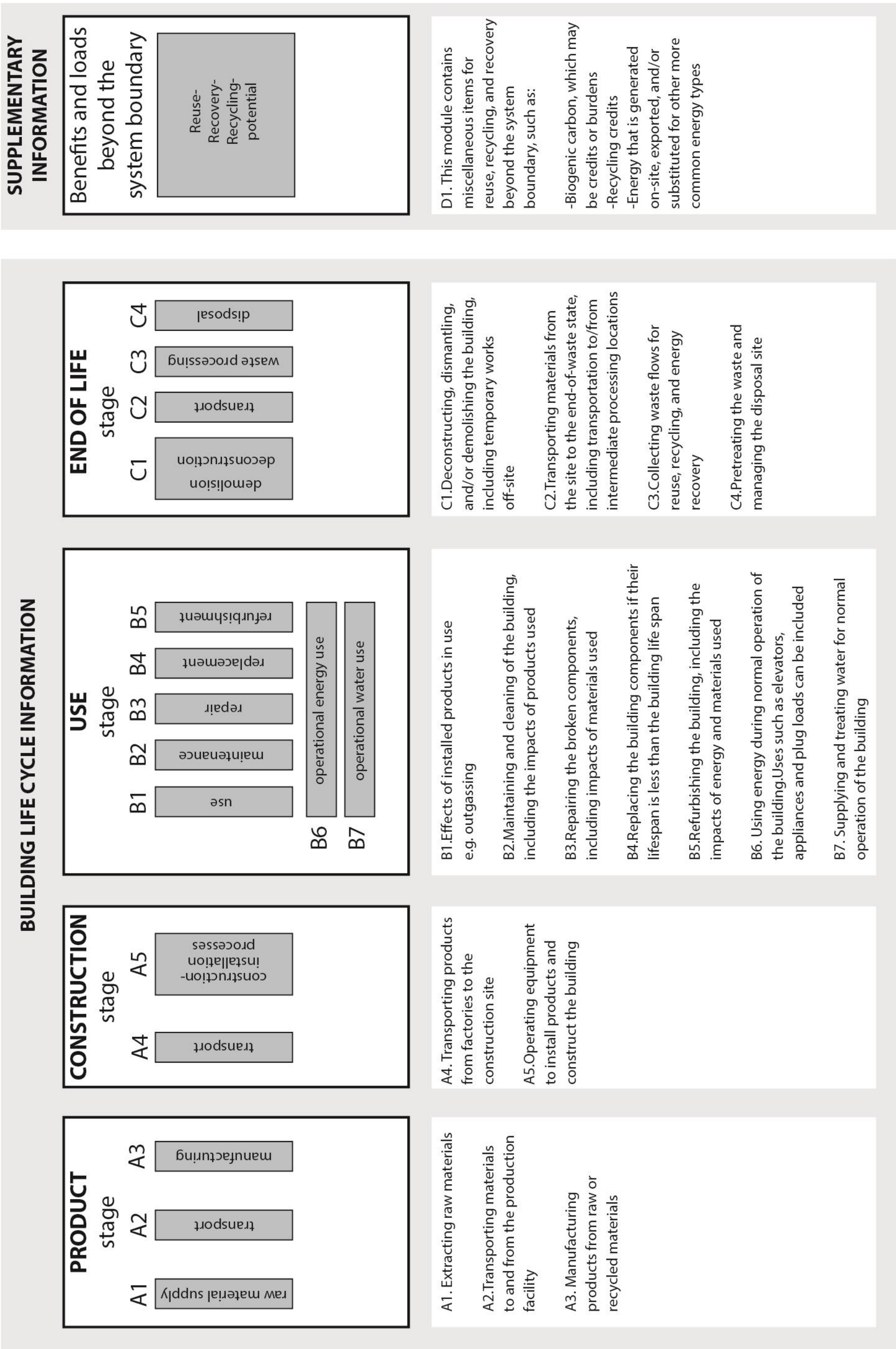

Figure 8: Standard life cycle stages and modules, adopted from EN 15978

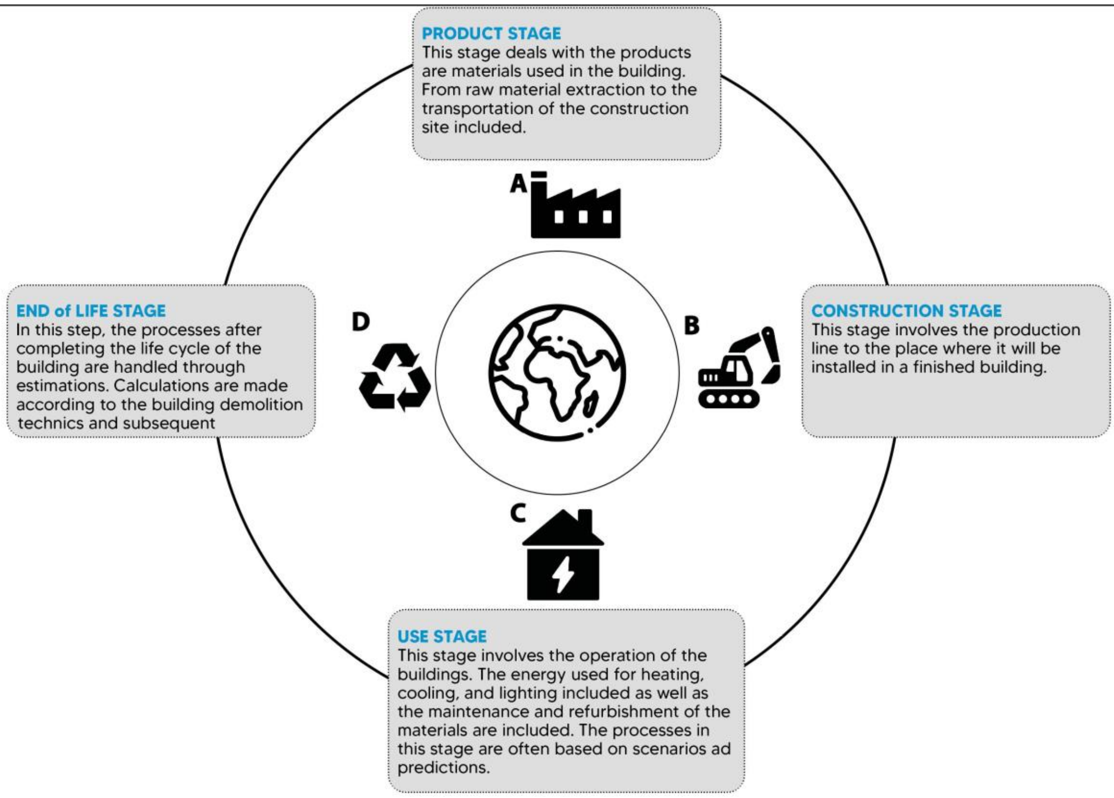

Figure 9: Life Cycle of a Building

5. Life Cycle Assessment of Buildings

Since the Life Cycle Assessment method was primarily developed for simple products, conducting an LCA for a building can be complicated. Because buildings are more complex systems that perform different functions in a longer life span. (Gervasio, Dimova, 2018)

LCA of buildings can be operated at 4 levels, the materials, and production level, the building level, and finally industry level. Material and production level LCAs are a consumer of the information to evaluate the materials and this helps them to make a selection among different products. At the building level, architects have the main role to conduct LCA, portraying the environmental impacts of their design or meeting regulations requirements. Industry-level LCAs often benefit policymakers and planners. (Simonen, 2014)

All of the material and process quantities in a building LCA are gathered into a set of data known as the inventory and compounded with the relevant effects for each material or process. The data collected are added together to determine a building's overall environmental effect. Figure 10 depicts a simplified illustration of the calculating procedure.

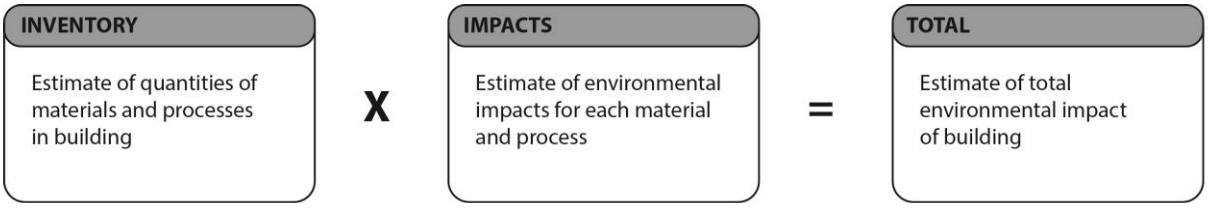

Figure 10: Simple explanation of LCA calculation method (Adopted from Life Cycle Assessment of Buildings: A Practice Guide, Carbon Leadership Forum)

6. Life Cycle Assessment Applications in the Buildings

This chapter is dedicated to presenting the studies where the Life Cycle Assessment methodology was implemented in the building sector. Since the application of the Life Cycle Assessment method to the buildings or building parts, they are worth mentioning. The following studies have been helpful to the research development of this study.

Adalbert, Almgren, Holleris, and Petersen, 2001 applied LCA to 4 buildings in Sweden to discover which life cycle phase has more environmental impact. They also researched whether there are similarities between environmental impact and energy use of the buildings. The assumed lifetime of the buildings was 50 years. Environmental impact categories were global warming potential, acidification, eutrophication, photochemical ozone creation potential, and human toxicity. According to the results of the LCA tool developed at the Danish Building

Research Institute, the highest environmental impact was observed during the occupation phase of the building with 70%-90% of the total. The second high-impact phase was manufacturing materials with 10%-20% of the total life cycle. The study shows that energy use and environmental impacts in five impact categories have similar distribution all over the building's life cycle. (Life-cycle assessment of four multifamily buildings. International Journal of Low Energy and Sustainable Buildings, 2, 1-21.)

Junnila, 2004, studied an office building in Southern Finland to compute the potential environmental impacts. The study purposed to determine which life cycle phases and elements contribute more to the total environmental impact. The result of the study shows that the stage operations (electricity, operations.) dominated the total impacts, in particular, the electric use and maintenance phase had a significant impact. On the contrary, the impact derived from building materials was less in comparison. (The environmental impact of an office building throughout its life cycle, 2004)

Blom, Itard, and Meijer, 2011, applied LCA to a Dutch welling, to assess the environmental burden of building-related and user-related gas and electricity consumption. According to the results of the study, the gas consumption of the building has a significant contribution to four environmental impact categories. By reducing the heating need of the building by 23%, total environmental impacts were reduced in the amount of 13%. However, in this case, electricity use dominates the total environmental impact. According to a study, if electricity consumption is reduced by 47%, the total environmental impact would decrease up to 45%. The conclusion of the study was, that since the electric consumption of the building can not be reduced, the environmental burden of the electricity could be reduced by changing the environmental impact of the electricity supply. (e. g. wind power) (Environmental Impact of Building-Related and User-Related Energy Consumption in Dwellings." Building and Environment 46.8 (2011): 1657– 1669. Web.)

(Rodrigues et al.. 2018) A study was conducted in Portugal, which aims to calculate embodied carbon and embodied energy of an industrial building with 6733 m^2 by using the LCA methodology. A gate-to-gate approach is followed in the study. According to the result with 508.57 kgCO2-eq/m^2 and an embodied energy of 4908.68 MJ/m2, it is determined that building materials contribute the most total embodied energy and embodied carbon. While materials with more process like metal and concrete have more impact on the total result, more natural materials such as wood, soil and stone has a lower impact on the total embodied energy and embodied carbon. Based on the results, it is possible to reduce the carbon footprint of the buildings by using fewer processes and materials. (LCA of constructing an industrial building: focus on embodied carbon and energy. Energy Procedia. 153. 420425. 10.1016/j.egypro.2018.10.018.)

(Dani, A.A. et al.. 2022) studied two residential buildings in the Auckland region in New Zealand by using the LCA method. The study aimed to compare and quantify carbon emissions derived from two buildings one is made of light timber and the other one is made of light steel. The service life of the buildings is determined as 90 years. Results of the study show that the emission of light timber house calculated at 13.72 kg per year while the light steel is 15.41 kg which is 12% higher than the timber one. (Dani, A.A.; Roy, K.; Masood, R.; Fang, Z.; Lim, J.B.P. A Comparative Study on the Life Cycle Assessment of New Zealand Residential Buildings. Buildings 2022, 12, 50.

(A. van Stijn et al. 2021) built a CE-LCA model to asses a building component in a circular system. A model system includes business-as-usual, reclaim, and plug-and-play alternatives. The business-as-usual variant is the representation of the current practice, made of melamine-coated chipboard has a life cycle of 20 years, is rarely renovated and at the end of its life, the kitchen is demolished. Only chipboard is used for its feedstock energy. The second variant is called reclaim! Which is very similar to the business-as-usual but replaced with non-virgin materials that are in their second life cycle. The total life cycle is reduced to 10 years. The third variant was designed with circular design strategies. It is a modular kitchen model where parts are sorted into different categories by their technical life spans. The cabinet includes a structural frame with a life span of 80 years, infills with a life span between 20 to 40 years, and finishing with a shorter life span of 20 years. This model is designed as demountable on the joining parts to provide different arrangements and reuse. At the end of life, the parts that have completed their use cycle are sorted by the manufacturer to be re-used, recovered, or recycled. This model is useful to close and slow down the loops in kitchen manufacturing. These kitchen variants were compared by applying LCA, to assess their environmental impacts. The conclusions were,

-The use of non-virgin materials could reduce the environmental impact but shorten the life cycle. Because these non-virgin materials also have an initial production impact, it is concluded that the use of non-virgin materials with an initial impact, is not preferable.

-The third variant called plug-and-play, performed the least impact on the environment thanks to the possibility of re-use of the parts, introducing more life cycles to the component.

(A Circular Economy Life Cycle Assessment (CE-LCA) model for building components, Resources, Conservation and Recycling, Volume 174, 2021)

(Eberhardt, van Stijn,Stranddorf,.Birkved,Birgisdottir,2021). A study focused on a building context that is dominated by concrete structures in Denmark. The reason was that concrete structures are more difficult to handle in a circular economic system since they are hard to reuse and the production phase is not very environmentally friendly.4 design variants are developed in comparison with a current business-as-usual structure system. The study focuses on the structure itself only, not including further finishing.

-Business-as-usual (BaU) variant is considered as reinforced concrete which is on-site cast. The life span of BaU is assumed as 75 years, at the end-of-life scenario is to be demolished and most of the concrete will be used for road-filling activities.

-ECO variant is narrowing loops by saving 22% and 25% concrete and reinforcement in comparison with the BaU variant by using the prefabricated and on-site cast method. The functional life span and end-of-life scenarios remain as BaU.

-The BIO variant is made of cross-laminated timber (CLT), dowelled joint with a life span of 50 years. It consists, of CLT walls and timber hollow core floor slabs. End-of-life scenarios are as follows; Timber floor slabs are recycled CLT walls element with 100 years of a technical life cycle, can be reused after 50 years, and finally burned for energy recovery.

-Design for disassembly (DfD) variant designed as demountable to prevent possible material loss during the end of life. The parts are easily reusable without any damage. It has both virgin and second use materials.75 years of life span is assumed with a possible four reuse of the elements (i.e., in four different locations) and finally, they are recycled.

-OPEN variant consists of prefabricated reinforced concrete walls and floor elements that are cast together. It has openings in the walls and floors filled with insulated timber frame wall panels and hollow core timber floor slabs. They can be replaced or removed within the openings according to the different designs of the rooms. The lifespan is 200 years with a change in infills every 50 years.at the end of life, concrete and timber are recycled.

Results showed that only ECO and OPEN variants performed less impact in all 11 environmental impact categories in comparison with the business-as-usual version. Components with a long functional technical lifespan perform better in terms of resource efficiency, and longer use cycles through adaptability, facilitating longer after-use. (Environmental design guidelines for circular building components: The case of the circular building structure. Sustainability, 13(10), [5621]. https://doi.org/10.3390/su13105621

7. CIRCULAR DESIGN STRATEGIES

This chapter aims to address circular strategies in the building sector. After a detailed literature review, it has been concluded that reuse and design for disassembly are the two prominent topics that needed to have discoursed.

7.1. Reuse

The actors of the construction sector are increasingly expected to take into account the environmental consequences of building projects. The environmental impacts of building material manufacture have received a lot of attention in recent years. Because the production stage of building materials may account for up to 50% of the environmental consequences of new and low-energy buildings across their whole life cycle (Douguet, 2021)

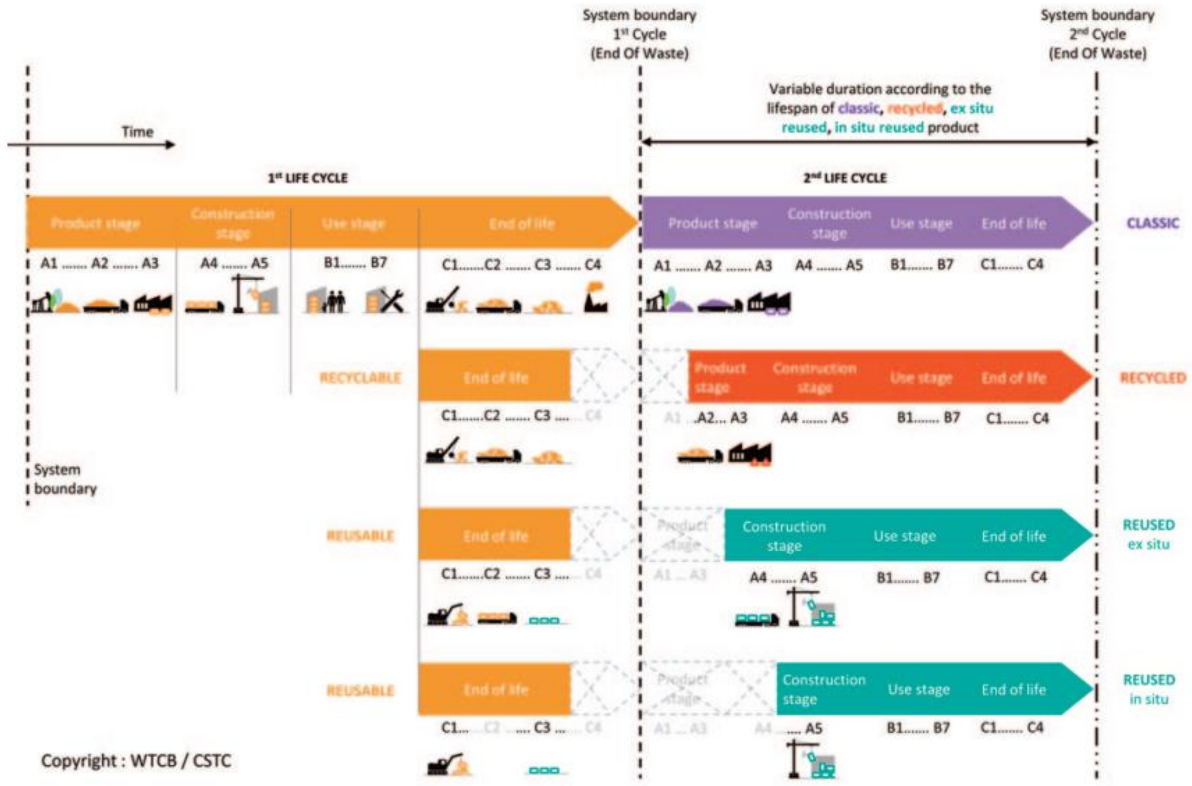

Diagram 004: The impact of recycling and reuse on life cycle modules

Figure 11: The impact of recycling and reuse on life cycle module, (The environmental impact of reuse in the construction sector, 2021)

Reusing can be a solution as a way to avoid the depletion of virgin materials and deal with building waste, which is another impact that will occur at the end of the building life cycle. As opposed to the production of new materials, reusing has many environmental advantages. Figure 11 illustrates how reuse can reduce environmental impacts derived from both raw material extraction and manufacturing stage.

7.2. Design for Disassembly (DfD)

The design for disassembly (DfD) technique has recently emerged as a current solution to demolition by improving disassembly activities to enable reuse. (Kissi, Ansah, Ampofo, Boakye, 2019) It has a lot of promise for promoting the circular economy.

Even though DfD concept can be considered relatively recent, EU Project Buildings as Material Banks (BAMB) and EPA(United States Environmental Protection Agency) defined the framework of this design process. In addition, multiple sustainable building certification systems award points for DfD.

DfD aims to ease the process of deconstruction at the hand of design and planning. Deconstruction is the process of dismantling a structure yet reusing the dismantled elements. The typical waste management procedure is fundamentally altered by the deconstruction process. The DfD method is an essential approach to raw material conservation.(Riosa, Chonga, Graua, 2015)

DfD introduces buildings that are designed for future alteration and ultimate dismantlement (in part or whole) for the recovery of equipment, parts, and materials. This design process comprises creating the necessary assemblies, components, materials, building processes, and information and management systems. Material recovery aims to maximize economic value while minimizing environmental effects through later reuse, repair, remanufacture, and recycling. (DfD Design for Disassembly in the Built Environment, 2005)

DfD may also be a smart method for avoiding obsolescence and reducing economic considerations (such as labor expenses) that drive destructive demolition and disposal of structures.

The main principles of DfD are: 1) Adequate reporting of the construction materials and strategies for deconstruction. 2) Design the connectors, and joints that ease the dismantling process. 3) Divide non-reusable, non-recyclable and non-disposal elements e.g. plumbing. 4) In order to ease the standardization of components, design basic forms and structures. 5) Type of design that reflects labor activity, safety, and productivity.

The following chapter is going to depict and illustrate the research and implementation methodology of this study.

CHAPTER 3: METHODOLOGY

This study used a Life Cycle Assessment method to analyse and compare the environmental impacts of current construction methods to achieve the aforementioned objectives. The scope of the study was to assess the unit processes with a “cradle-to-grave” approach which included the stages such as material extraction, manufacturing, transportation, on-site construction and installation, and the end-of-life phases. 3 end-of-life scenarios were created with the aim of comparing the business-as-usual and circular building practices. These three scenarios were implemented in the case study project and later on environmental impacts of the scenarios were compared by using the Life Cycle Assessment method. The methodological framework of this study is divided into 3 phases: Research, Scenarios Building, and Implementation. In Phase 1, circular economy principles are assessed and required data for scenario building is extracted. Literature review regarding the life cycle assessment of buildings and/or components was assessed by using bibliometric analysis methodology. With the help of the Literature Review, in Phase 2, life cycle scenarios were created. Life cycle scenarios are defined in order to compare business-as-usual and circular variants in the construction industry. Finally in Phase 3, with the help of ISO standards to conduct a Life Cycle Assessment, the environmental impacts of the scenarios were calculated. Later on, the interpretation of the results is presented. In this study, environmental impacts are studied in five categories; global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and smog formation potential. Three different end-of-life scenarios are compared to evaluate different impacts on the environment. (1)-demolished and landfilled at the end of life, (2) recycled at the end of life, and (3) components reused at the end of life. Scenario I represents the business-as-usual building life cycle, whereas scenario II and III implements circularity principles at the design stage or at the end of life.

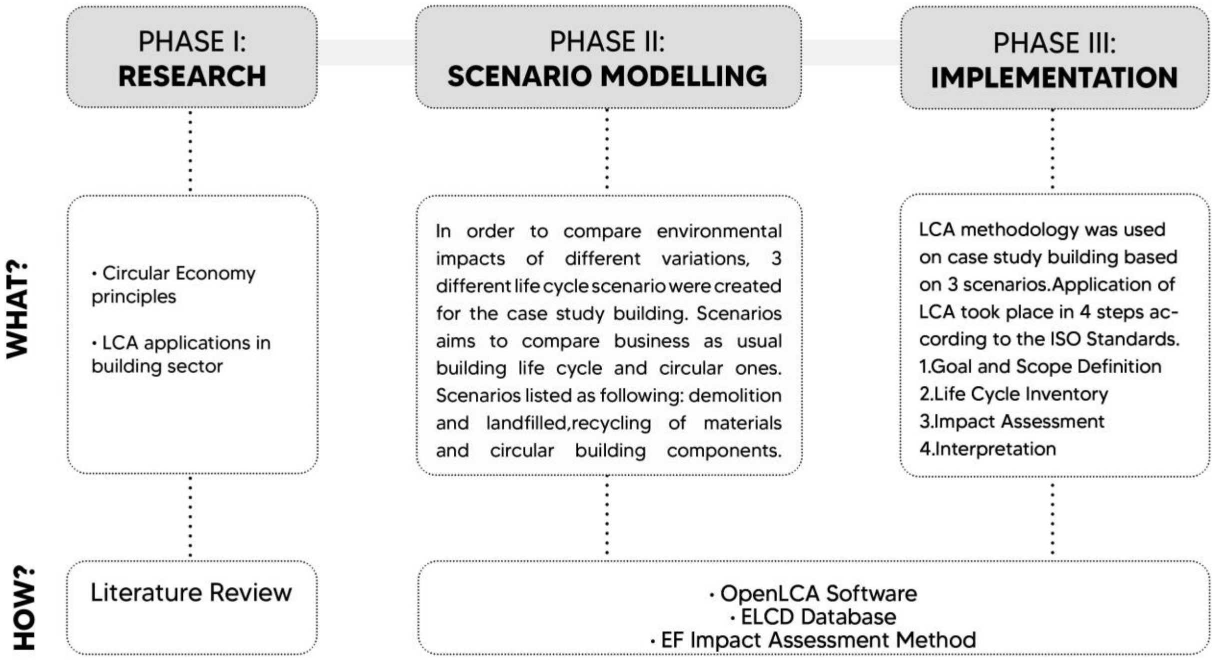

Figure 12: Methodological framework representation

3.1. Goal and Scope Definition

The main goal of this study is to quantify the environmental impacts of a commercial office building based on 3 different end-of-life scenarios by implementing the Life Cycle Assessment (LCA) methodology. End-of-life scenarios were created with the aim of comparison business as usual practices and circular economy principles. With the help of the implementation of Life Cycle Assessment (LCA) to the scenarios, this study aims to investigate whether the adaptation of circular economy principles could reduce the environmental impacts of a building or not. Further defined the scope of the study includes an overview of the life cycle of a building from raw material extraction to the different end of scenarios.

3.2. System Boundaries

This study consists of 3 different Life Cycle Assessments since 3 different scenarios were evaluated. For Scenario I, the system boundary starts with raw material extraction and ends up with the demolition of the building. As an end-of-life treatment, Scenario I includes landfilling of the demolition waste. Whereas Scenario II has a similar system boundary nonetheless after demolition, materials are going to be recycled. Scenario III correspondingly starts with the raw material extraction although building components are considered circular. As a consequence of this, Scenarios II and III adopt system expansion for the life cycle impact calculations. To further define the lifespan for each scenario, was considered 50 years. All of the resources and energy consumed during production, manufacturing, transportation and finally demolition are taken into account as well as the consumptions during the service life of 50 years.

3.3. Functional Unit

The functional unit is a detailed description of the product or system being evaluated, so that the resulting LCA may be directly compared to the LCA of a similar product or system. (The American Institute of Architects, 2010) The functional unit can be optionally chosen for product-level calculations based on the product and life cycle phases evaluated. However, whole building Life Cycle Assessment studies show that results are provided for the whole building and/or per 1 m2 of the building area. Therefore, this study utilized a functional unit as one square meter (1 m2) of floor area.

3.4. Case Study Building

During the research period of this study, I had a chance to work as an intern at UNStudio in Amsterdam. As this study needed a building that is in the design phase, UNStudio granted me the case study building. The case study building designed by UNStudio is located at the central location of the company Adolf Würth GmbH & Co in Künzelsau-Gaisbach, a multi-layered campus has emerged over the past decades, which reflects the successful development of the company. The proposal by UNStudio is a hybrid-structure building in which the structure of the high-rise building is built in wood, and the base stories are wood-concrete composite construction. The first construction phase consists of a vertical office block with low floors and a podium with up to 3 floors and an airy inner courtyard. The position and orientation of the vertical office block were chosen in such a way that it offers a vertical orientation in the middle of the otherwise horizontal and flat building structure in its long-distance effect and forms a clear centrum of the campus. The plinth construction mainly houses the visitor center and is formed around a spiral-shaped inner courtyard, which brings nature into its center like an oasis. The outwardly orthogonal building cubature becomes soft and porous on the inside. The curved inner courtyard around a grove of trees as a central place for the community continues as a vertical outdoor space along the high-rise facade. A lively and diverse working environment is created here at the interface between inside and outside.

Figure 13: Wurth Campus by UNStudio, Inner Courtyard

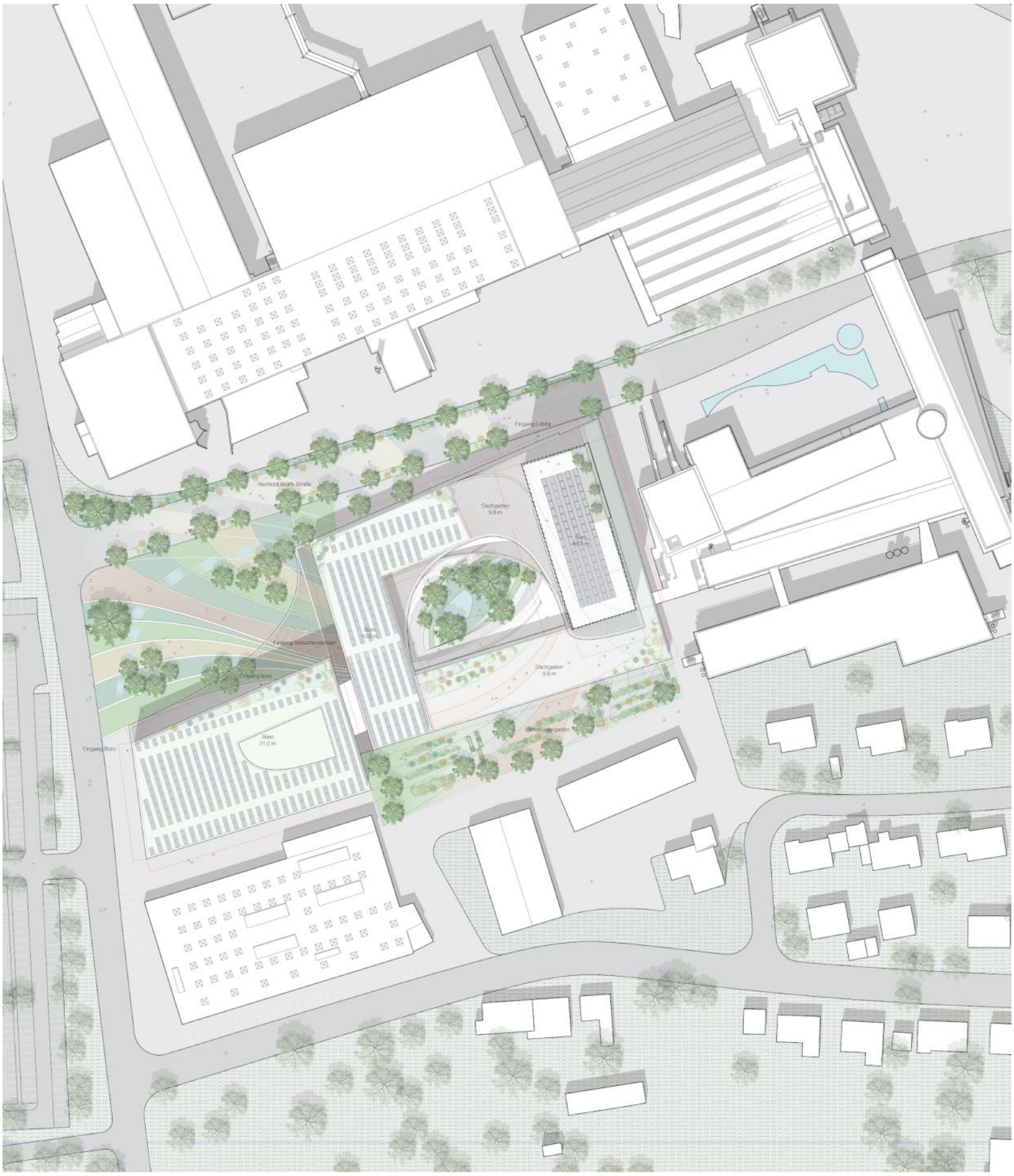

Figure 14: Site Plan

The inner courtyard and vertical outdoor space together form the iconographic momentum of the building. The curved section in the façade is a subtle reference to the Würth company logo and thus combines identity with unique quality for work and living space.

Figure 15: Wuerth Campus interior view

The building blends into the overall picture of the campus in terms of its external appearance thanks to its outwardly cubic design language and the white facade, and yet appears as a special building block due to its detailing. While the focus on the outside is on the integration into the campus and its central regulatory role as a landmark in the long-distance effect, on the inside, with its round and gentle design language and the intense green, the focus is on people, their needs, and the community. Green and nature are integral components of the design canon and testify to the biophilic claim that ensures the social, physical, and mental health of all users. The modular grid of the supporting structure made of wood shimmers through the faceted, transparent facade and gives the otherwise technical appearance a warm touch. On the inside, wood then becomes the dominant material in the roof landscape of the inner courtyard. The use of wood as a material of the future also points to the innovative claim of the building. Tradition coupled with innovation and knowledge is combined into one concept.

Building Parameters	Specifications
Storey height	3.5m
Service life	50 years
Gross floor area	47724 m^2
Structure	Timber(glulam)
Envelope	Glass façade elements
Foundation/basement	Concrete
Walls(interior)	Timber

Table 3: Case study building parameters

3.5. OpenLCA Software

In this study, in order to compare environmental impacts, three life cycle scenarios were modeled in OpenLCA version 1.11 software. The background system was modeled with the ELCD 3.2 (European reference Life Cycle Database) From EU-level industry organizations and other sources, the ELCD database contains Life Cycle Inventory (LCI) data for important commodities, energy sources, transportation, and waste management. The appropriate industry organization has approved and submitted the pertinent data sets.

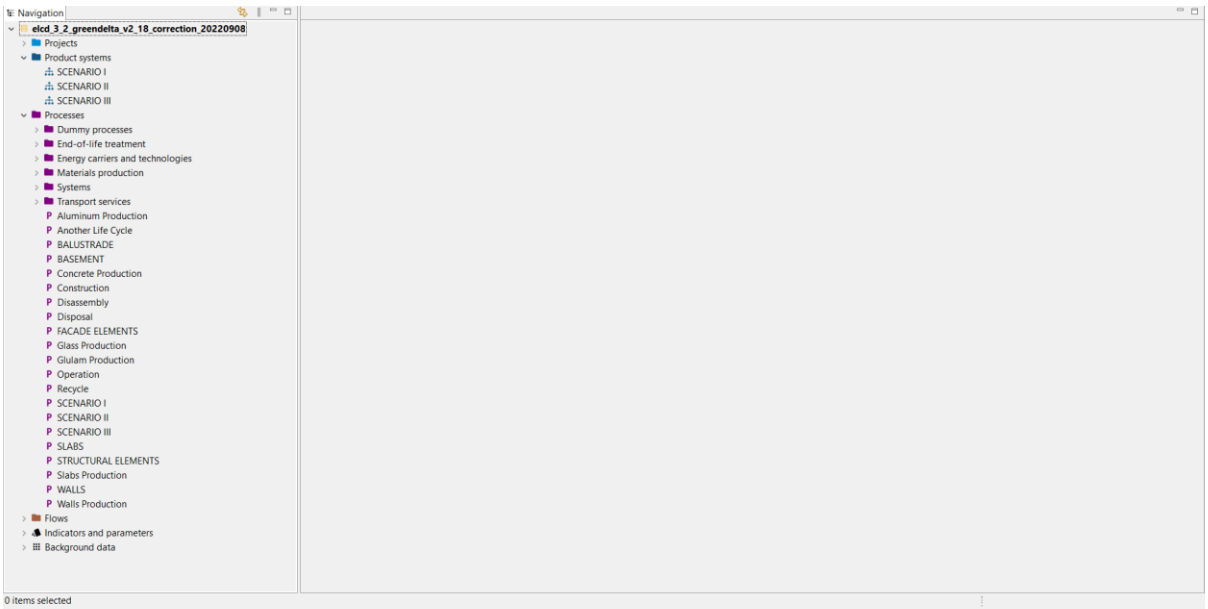

Figure 16: ELCD database overview on OpenLCA software

Subsequently, total environmental impacts are quantified by using the EF 3.0 (Adapted) impact assessment method. Results are quantified in five LCA impact categories: Acidification potential, climate change potential, eutrophication potential, ozone depletion, and photochemical ozone (smog) formation.

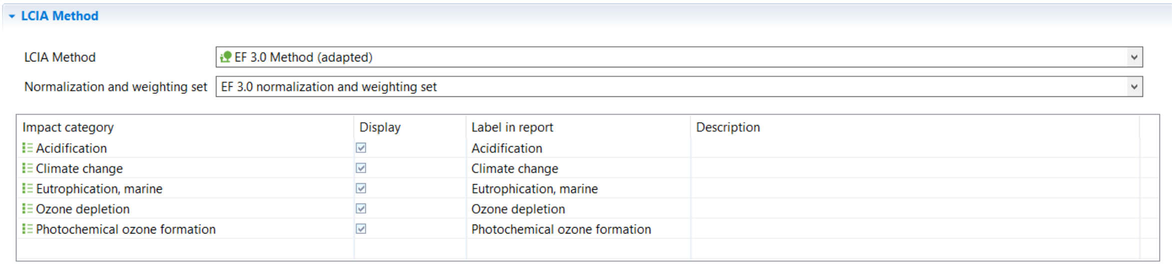

Figure 17: LCIA Method on OpenLCA Software

3.6. Service Life

Lifespan, or in other words, the service life of a building determined by how long the building tends to be used by the users. For the Life Cycle Assessment studies, it is mandatory to set a service life of the building. The operational consumptions of a building such as electric use, water use, and waste must be taken into account for more precise results.

The service life of the buildings varies from 25 to 100 years in the literature but the general trend is 30-50 years. It is recommended to keep the lifetime shorter, therefore it is more beneficial in terms of setting climate change goals for future decades. Furthermore, after careful analysis of similar life cycle assessment studies, the service life of the assessed building was considered as 50 years. Operational consumption calculations were based on a 50-year lifespan and included 3 scenarios.

3.4. Impact Categories

According to the ISO Standards, when performing Life Cycle Assessment, it is mandatory to specify impact categories that are going to be looked upon. Impact categories can be listed in three categories as follows: resource use, ecological consequences, and human health. This study is going to focus on the impact categories related to climate change so that ecological consequences. Therefore, considered impact categories in this study are, acidification potential, climate change potential, eutrophication (marine) potential, ozone depletion potential, and photochemical ozone formation potential. These impact categories in the proposed approach are the ones provided by the CEN TC 350 standards for the sustainability assessment of construction works. (European Commission, 2018)

Impact Category	Unit
Acidification potential	mol H+ eq
Climate change potential	kg CO2 eq
Eutrophication (marine) potential	kg N eq
Ozone depletion potential	kg CFC11 eq
Photochemical ozone formation potential	kg NMVOC eq

Table 4: Impact categories and units

Impact categories listed above are taking into account the whole life cycle of the building, from material production to end of life. In the second and third scenario, activities beyond the system boundary are also included in the calculations.

3.7. Life Cycle Inventory Analysis (LCIA)

This phase includes data collection and definition of the production quantities necessary for the life cycle impact assessment. Since buildings are complex structures where various materials and layers are stored, to perform an LCA, plentiful data regarding the materialization and processes need to be inserted into the software. For the simplification of the data inventory, the case study building was divided into 6 components to be dealt with; structure, slabs, façade elements, interior walls, balustrades, and finally foundation. Each component is later divided into sub-branches to list the elements, materials, and processes that are composed of. Figure 18 illustrates the breakdown strategy of the building components. It is necessary to mention that, this study in particular focuses on the comparison of different end-of-life scenarios and their relative impact on the total environmental burden. Since the benefited case study building is only in the conceptual design phase, the data regarding the materialization is quite limited. To simplify the inventory, some quantities and materialization data are based on estimations. For instance, since no realistic manufacturing process is available, the manufacturing location of each material is considered Germany. For each material, the transportation distance from the manufacturing place to the construction site was always considered 100km.

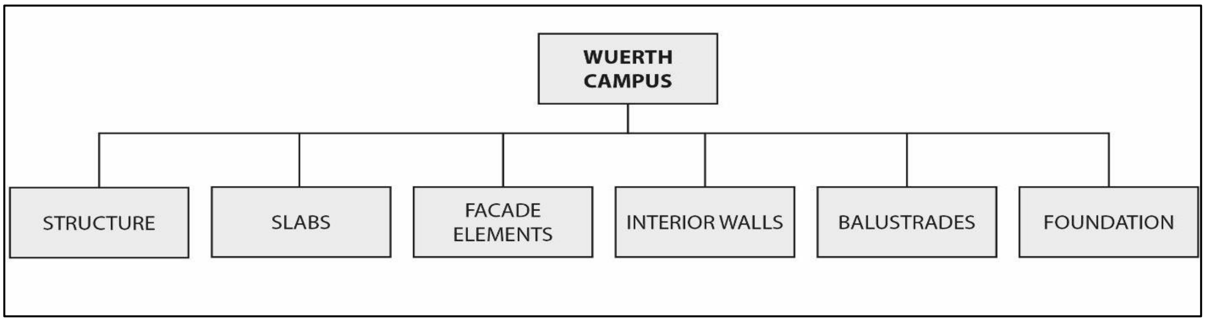

Figure 18: Breakdown of building components

3.7.1. Structural Elements

As the diagram illustrates in Figure 19, the building was designed with a timber structure. Due to the design decisions of the building, the dimensions of the structural elements vary in different parts of the building. Life Cycle Inventory requires a total quantity of the product used in order to assess the impacts. In order to quantify the total amount of wood that needs to be produced, each frame (set of columns and beams) is listed and the total volume of wood is then calculated. The structural system of the building consists of 10 different types of grids. Each grid includes columns and beams. The quantity of the grids and volumes are listed and the volume of each grid is included in the total volume calculation. The total volume of the different grids is summed and then converted to kilogram units. OpenLCA software supports the input data for the wood products in kg units. For the conversion, 1 m3 of timber is considered 576 kg. Table 5 illustrates the detailed quantification of the timber structure calculation. For the manufacturing of timber structures, glulam is preferred due to its load-bearing capacities. The total glulam amount is calculated as 3.435.321, 60 kg, and inserted into the software as input.

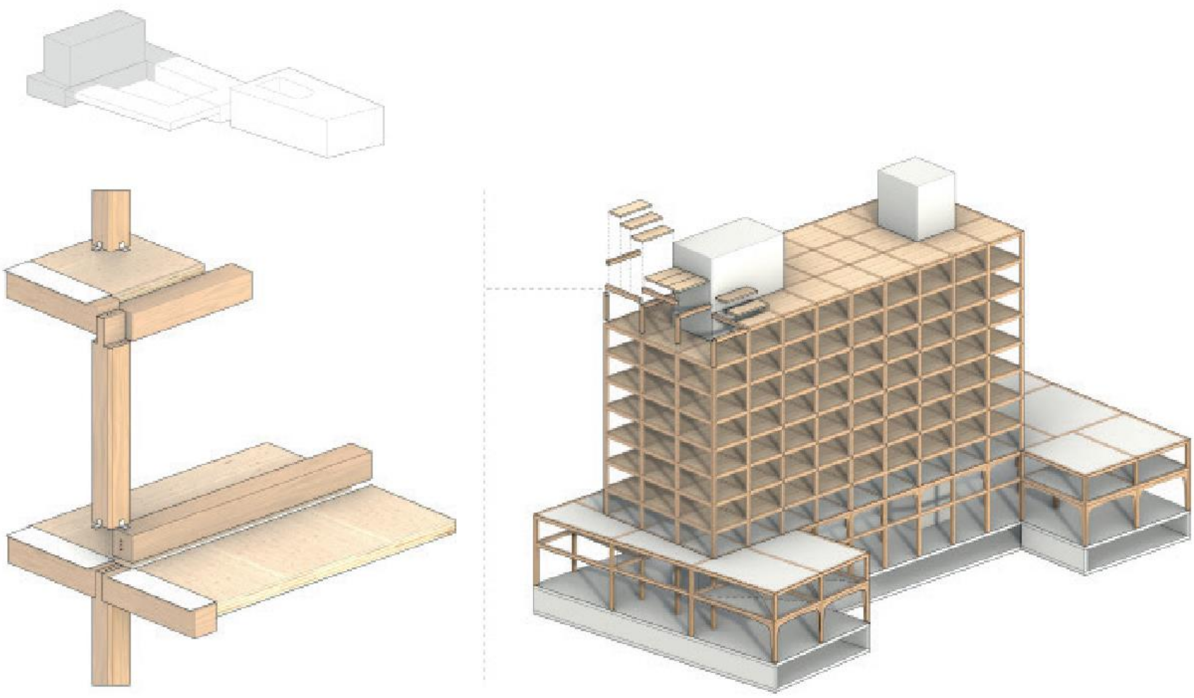

Figure 19: Würth Campus timber structure illustration

The structural system of the building consists of 10 different types of grids. Each grid includes columns and beams. The quantity of the grids and volumes are listed and the volume of each grid is included in the total volume calculation. The total volume of the different grids is summed and then converted to kilogram units. OpenLCA software supports the input data for the wood products in kg units. For the conversion, 1 m3 of timber is considered 576 kg. Table 5 illustrates the detailed quantification of the timber structure calculation. For the manufacturing of timber structures, glulam is preferred due to its loadbearing capacities. The total glulam amount is calculated as 3.435.321, 60 kg, and inserted into the software as input.

GRID TYPE	DIMENSIONS	QUANTITY	UNIT VOLUME	TOTAL VOLUME
	6x6x6 m	296	9,90 m3	**2930,40 m3**
	12x9x3.8 m	36	13,70 m3	**493,20 m3**
	12x12x6 m	75	17,30 m3	**1297,50 m3**
	12x9x6 m	24	27,40 m3	**657,60 m3**
	12.75x12x3.8m	6	15,50 m3	**93,00 m3**
	12,75x12x6 m	6	17,70 m3	**106,20 m3**
	13,5x13,5x3,8 m	10	15,90 m3	**159,00 m3**
	13,5x13,5x6 m	6	23,60 m3	**141,60 m3**
	6x9x3,8 m	8	10,70 m3	**85,60 m3**
	6x9x6 m	3	12,80 m3	**38,4 m3**
TOTAL m3				**5964,10 m3**
TOTAL kg				**3.435.321,60 kg**
*1m3 glulam equals to 576kg				

Table 5: Quantity measurements of structural system for the total glulam production

3.7.2. Slabs

This chapter is dedicated to the timber slabs of the building where the floors above the ground have. Concrete slabs in the underground will be examined later in the relevant chapter. With the help of the 3D model, the total area of slabs was calculated as 47.724 m2. Timber slabs are considered to be manufactured of cross-laminated timber due to the technical features of the material. Therefore, the manufacturing of the slab elements is divided into two parts, slabs, and timber beams.

3.7.3. Facade and Windows

The building consists of several façade elements with different dimensions as well as timber structure grids. Parallel to the quantification of data from the timber structure, the same technique is applied to sum up the total amount of materials necessary to produce the façade elements. 9 different typologies of the façade unit are listed, and the surface area of the total glass is calculated and added then to the total glass area. Façade elements are a composition of glass and aluminium structure. Therefore total quantitation of the façade modules is composed of glass and aluminium amount. Table 6 illustrates the total quantities required for glass and aluminium production. The total weight of the glass is calculated as 906,854 kg whereas the total weight required for the aluminium is 908,267 kg. Relevant processes are inserted in the life cycle model for the manufacturing of aluminium and glass with the calculated amounts.

FACADE ELEMENT	QUANTITY	UNIT AREA	TOTAL AREA
	169	17 m²	2873 m²
	181	12 m²	2172 m²
	142	12,5 m²	1775 m²
	286	12,6 m²	3603,6 m²
	281	37m²	10,397 m²
	19	29 m²	551 m²
	796	5 m²	3980 m²
	173	15 m²	2595 m²
	37	3,8 m²	140,6 m²
TOTAL AREA m²			**27947m²**
TOTAL VOLUME OF ALUMINUM			**336,52 m³**
TOTAL WEIGHT OF GLASS			**906,864 kg**
TOTAL WEIGHT OF GLASS			**908,267 kg**
*Total weight of the materials are based on assumptions.			

Table 6: Quantity measurements of façade elements for the total production

3.7.4. Interior Walls

The project consists of timber division walls on the floors above the ground and concrete walls underground. This chapter is going to explain how the timber structure walls are included in the total calculations. Based on the 2D drawings and 3D model of the project, the total area of the timber walls was calculated as 2.022 m2 In addition to the manufacturing processes of the walls, the manufacturing of gypsum plaster is included. No wall paint was considered in this study due to the limitations of the database. Since ELCD is a free database, it does not contain all the related data for construction and manufacturing.

3.7.5. Balustrades

The project has balustrades in several locations therefore they are also included in the life cycle inventory. The balustrade is divided into 2 parts as follows: transparent (glass) parts and handrail (aluminium) parts. The total area of the glass and aluminium is taken into account. Total area converted to the kg unit in the OpenLCA software. Table 7 illustrates the total amount of aluminium and glass inserted as the input for manufacturing processes.

Item	Area	Weight
Total area of the glass	553,6 m2	70 kg
Total area of the aluminium	25 m2	67,5 kg

Table 7: Quantity measurement for balustrades

3.7.6. Basement and Foundations

The building has 2 story underground which has been designed with a concrete structure. The structure, slabs, and walls are made of concrete. However, with the aim of simplification of the impact assessment and due to the lack of data regarding this part of the building, inventory analysis of the basement is based on the total surface area. The total surface area of the basement floor is summed up as 8,087 m2. Subsequently, pre-cast concrete has been chosen from the database and the total area of the concrete is inserted as input data.

4. Operational Phase

One of the most impactful life cycle stages of a building is the operational phase, in other words, the use phase. This phase includes energy consumption, water use, and waste generation throughout the all service life of the building. Since during this phase a great amount of energy is being spent and it contributes to resource depletion, it is highly important to consider the total amount of energy during the phase. Besides that, all the repairing and replacement activities during the life cycle of the building elements must also be taken into account including the transport of the equipment in order to do so. (The American Institute of Architects, 2010) While it is crucial to know the energy requirement per m2/year in kWh or MJ necessary for the operation of the building, the composition of the energy supply matters as well. Impacts may differ according to the technology being used for the production of electricity and heat.

In this study, energy consumption, water use, and total waste generation are included in the operational phase calculations. The main focus of this study is the alternation of the end-of-life scenarios and the operational phase consumptions are identical for each scenario.

Consumption quantities are based on assumptions and not calculated in a realistic way since they do not affect the relative results of total environmental impacts. In order to simplify the calculations, repair and replacement processes in this stage are neglected.

CHAPTER 4: SCENARIO MODELLING AND RESULTS

After the life cycle inventory, collected and processes are inserted in the life cycle scenarios. For each scenario, processes are organized by the following order, acquisition of materials, manufacturing, use, and demolition. All the transportation processes are taken into account. Since there are three scenarios with different end-of-life scenarios, the processes from raw material acquisition to the end-of-life are identical. In order to define the impacts of the processes, background data was chosen by using the ELCD 3.2. Database. Later on, life cyle impacts are calculated using EF 3.0. Impact Assessment method. Results are listed in five impact categories. Figure 20 illustrates the workflow of the Life Cycle Assessment from this study.

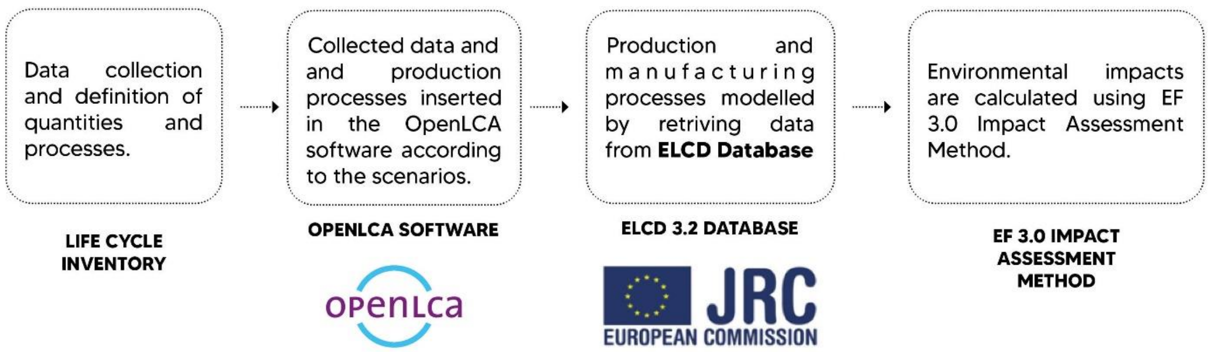

Figure 20: LCA workflow

The following chapter is going to demonstrate each scenario in detail and present the life cycle inventory of the scenarios. Following the scenarios, Life Cycle Impact Assessment results are presented for each scenario.

This study aims to assess 3 different life cycle scenarios with different end-of-life scenarios applied to an office building. Scenarios were based on a comparison among conventional building life cycles and the ones adopted to circular economy principles. For each scenario, the same materials and components are taken into account and the life span of the building is considered as 50 years. Besides that, the construction and operational phase are identical for each scenario whereas end-of-life treatments of the scenarios differ. In this way, circular end-of-life treatments such as recycling or design for disassembly, are going to be assessed in terms of their impact on the total life cycle. Table 8 illustrates the differentiation between the life cycles.

SCENARIO	**SERVICE LIFE**	**END OF LIFE TREATMENT**
Scenario I	50 years	Landfilling
Scenario II	50 years	Recycling
Scenario III	50 years	Reuse of components

Table 8: Assessed life cycle scenarios

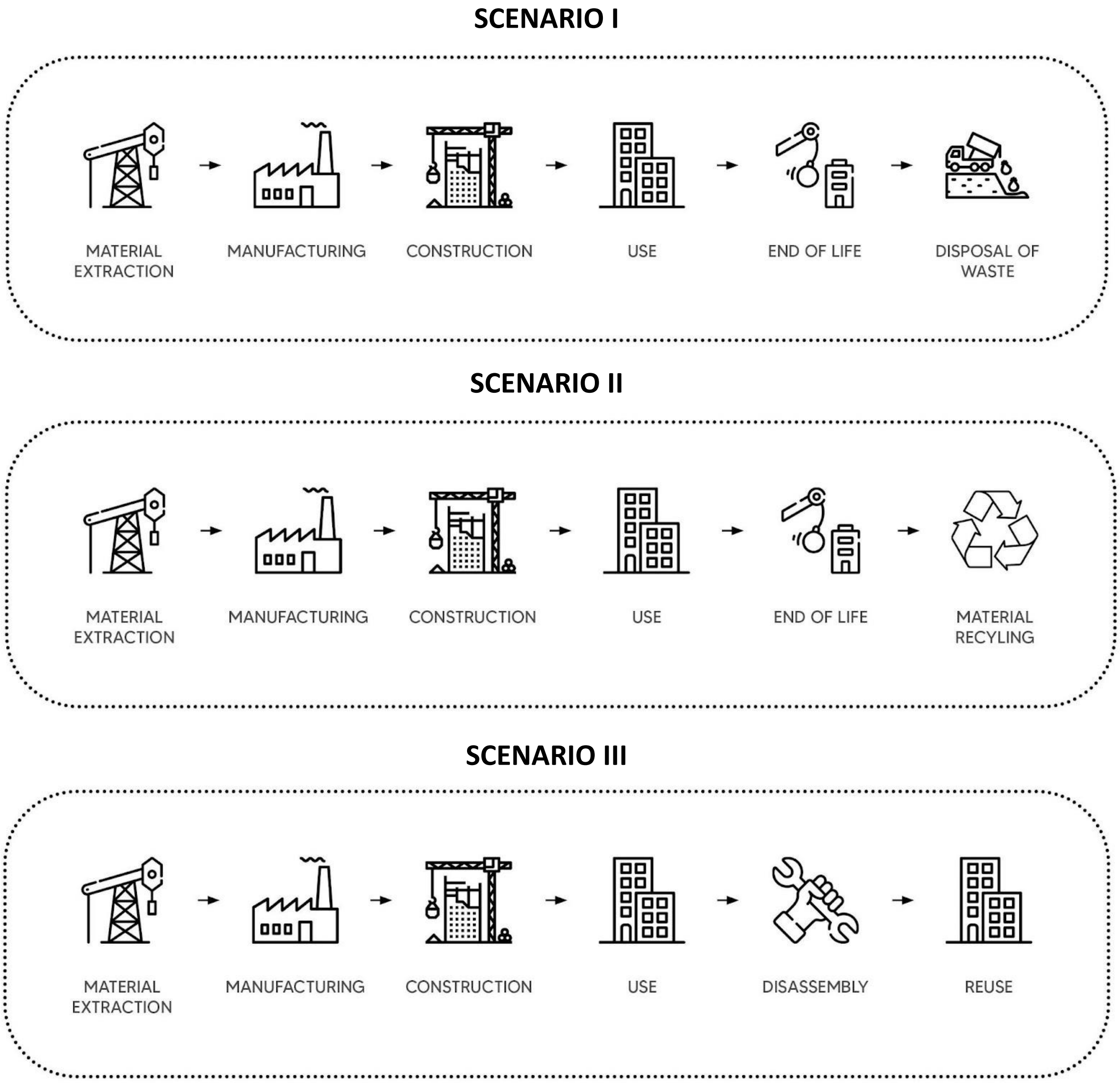

Figure 21: Three life cycle scenarios assessed

4.1. Scenario I

Scenario I consist of the system boundary from raw material extraction to the demolition stage of the building. The life cycle stages considered are; raw material extraction, construction, operation, and demolition. The end-of-life scenario of Scenario I includes the disposal of the demolished building material. Demolition waste of glass, concrete, and wood is landfilled. This scenario represents the business-as-usual building life cycle in the construction sector. No circularity is considered in this scenario.

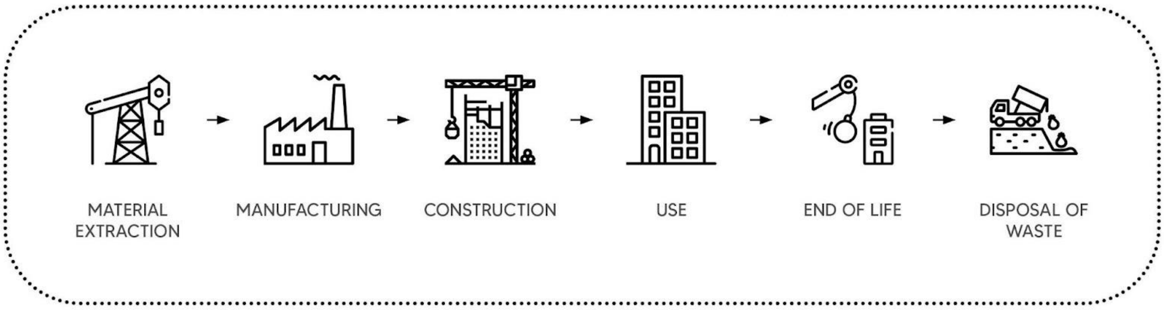

Figure 22: Scenario I Life Cycle Stages

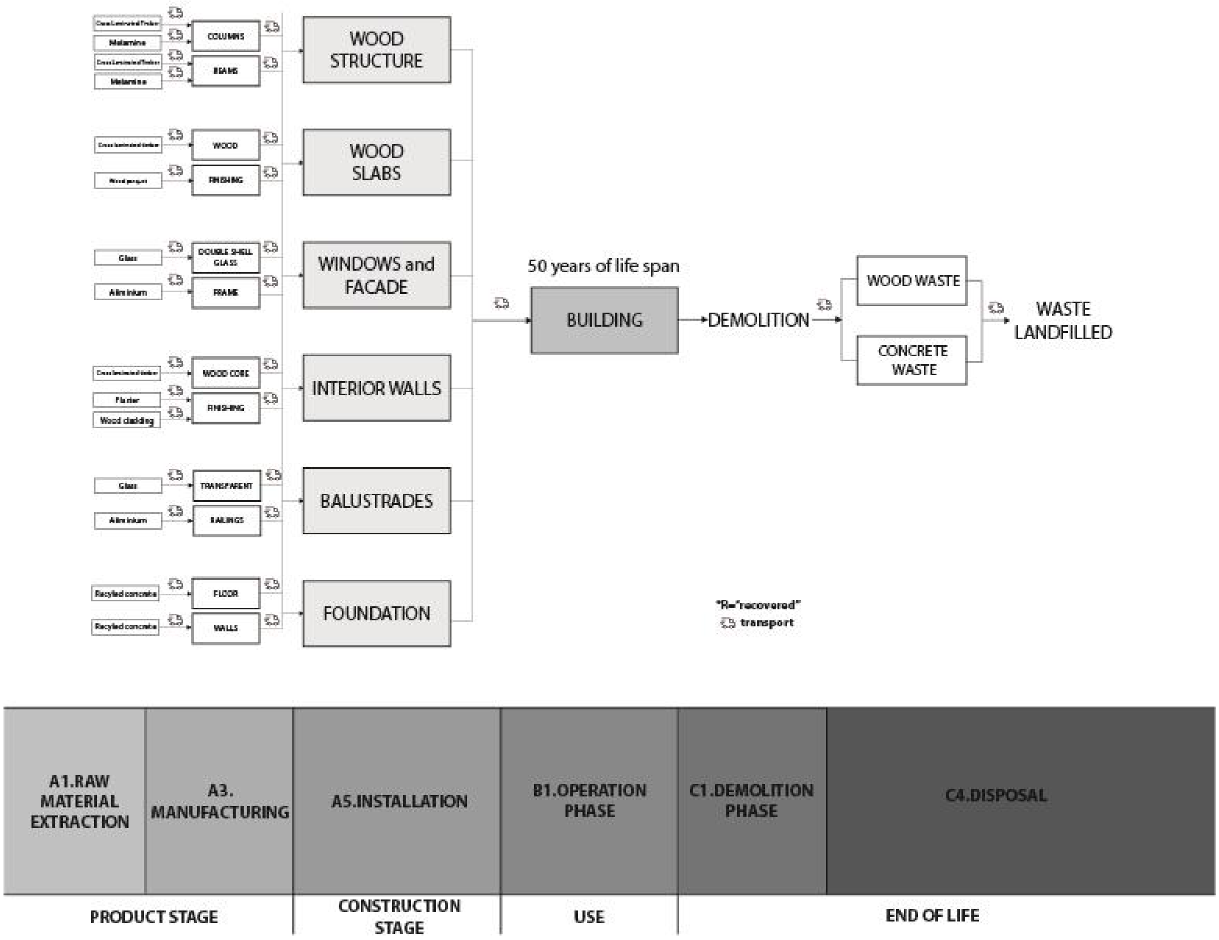

Figure 23: Simplified flowchart of Scenario I

Figure 23 illustrates the life cycle flows of Scenario I. Considered life cycle stages are explained. For each stage, the contribution of the emissions derived from transportation is also included.

Table 9 shows the Life Cycle Inventory (LCI) of Scenario I in order to perform the impact assessment. Quantity data for the Life Cycle Inventory is provided by the designers and 3D computer models. Whereas the data regarding specific activities like production flows are derived from the literature review.

Scenario	Parts	Life Cycle Stage	Material	Description	Amount	Unit	ELCD Database
SCENARIO I	STRUCTURAL ELEMENTS	A1,A3	Glulam	Pinewood	3.43532 1E7	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		Heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	30000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		Transport[1]	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	SLABS	A1,A3	Slabs	Pinewood	14317.0	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		Transport*	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Beams	Pinewood	725	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		Transport*	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	FACADE ELEMENTS	A1,A3	Aluminium	Aluminium production	908	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	906	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		Transport*	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	WALLS	A2	Wall Structure	Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A2		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A1,A2		Pine wood	2022	kg	Pine wood, production mix, at saw mill, timber, 40% water content - DE
		A2		Water	500	kg	Dummy_Water for industrial use
		A1,A2	Plaster	CaSO4	300	kg	Gypsum plaster (CaSO4 alpha hemihydrates), production mix, at plant, via calcination of calcium sulphate dihydrate, grinded and purified product - DE
		A2		water	500	kg	Dummy_Water for industrial use
	BALUSTRADES	A1,A3	Aluminium	Aluminium production	67.5	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	70	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	2000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	1500	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		Transport*	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BASEMENT	A1,A3	Pre-Cast Concrete	Pre-cast concrete	300	kg	Pre-cast concrete, production mix, at plant, minimum reinforcement, concrete type C20/25, without consideration of casings - RER
		A2		Transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BUILDING OPERATION*	B6	Domestic Use	electricity	200000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		B1		Biodegradable waste	-2000	kg	Landfill of biodegradable waste, at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
		B1		Municipal waste	- 200000	kg	Landfill of municipal solid waste, BE, DK technology mix, at landfill site, landfill including landfill gas utilisation and leachate treatment, without collection, transport and pre-treatment - EU-27
		B6		Natural gas	10000	kg	Natural Gas Mix, consumption mix, at consumer, technology mix, onshore and offshore production incl. pipeline and LNG transprt - EU-27

	B7		Water	-10000	kg	Waste water treatment, at waste water treatment plant, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment - EU-27
BUILDING CONSTRUCTION*	A5	Construction Activities	Different pollutants	250	kg	No provider is available for elementary flows.
	A5		electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
	A5		heat	50000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
	A4		Transport(5x)	5*100	T*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	A5		Demolition waste	500	kg	No provider available in the database.
BUILDING DISPOSAL	C3	Disposal Activities	landfill of biodegradable waste	-300	kg	Landfill of biodegradable waste, at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
	C3		Landfill of glass/inert waster	-906	kg	Landfill of glass/inert waste, at landfill site, landfill including leachate treatment and without collection, transport and pre-treatment - EU-27
	C3		Landfill of plastic waste	-200	kg	Landfill of plastic waste, at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
	C3		Landfill of wood products	-3.43532 1E7	kg	Landfill of wood products (OSB, particle board), at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
	C3		Municipal solid waste deposition	-100	kg	Landfill of municipal solid waste, FR, GB, IE, FI, NO technology mix, at landfill site, landfill including landfill gas utilisation and leachate treatment, without collection, transport and pre-treatment - EU-27
*For the processes/products which do not exist in the ELCD Database, the closest available process/product is selected.						
* The procedure of end-of-life (EoL) in the OpenLCA software, the Opposite Direction Approach (ODA) is used.						
[1]The distance for the transportation is assumed 100 km for each process.						
*Consumptions in the operation phase are based on assumptions since they do not affect the relative results.						
*Processes in the construction phase are based on assumptions since they do not affect the relative results.						

Table 9: Detailed LCI of Scenario I

4.1.1. Scenario I Results

Impact Category	Unit	Impact Result
Acidification potential	mol H+ eq	1.25819E5
Climate change potential	kg CO2 eq	2.80329E7
Eutrophication (marine) potential	kg N eq	1.74156E4
Ozone depletion potential	kg CFC11 eq	1.06505
Photochemical ozone formation potential	kg NMVOC eq	4.43276E4

Table 10: Impact results of Scenario I

Scenario I represents the business-as-usual life cycle scenario where the building waste is landfilled once the lifespan of the building is completed. Table 10 illustrates the total environmental impacts in 5 selected categories derived from Scenario I. These results address the total impact of the all life cycle stages.

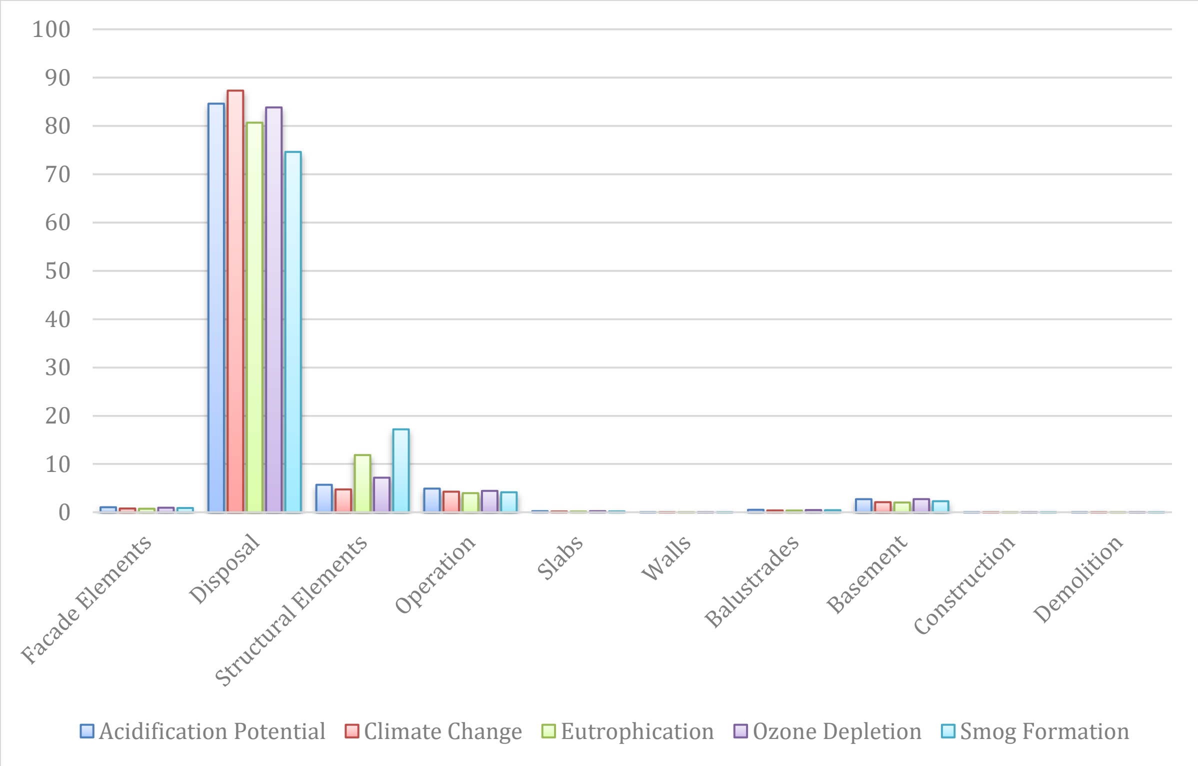

Figure 24: Scenario I contribution of processes

Figure 24 illustrates the contribution tree of the processes to LCIA results. The most contributing activity to the impacts is the disposal stage of the building. This is due to the waste which was generated as a result of demolition activities. Since no circularity principles are used in this scenario, due to the landfilling of the building waste, high environmental impacts are observed.

4.2. Scenario II

Scenarıo II consists of the system boundary from raw material extraction to the demolition stage of the building as well as the Scenario I. Life cycle stages considered are; raw material extraction, construction, operation, and demolition. However, the end-of-life treatment for Scenario II comprises the recycling activities of the demolition waste. In this scenario, once the building is demolished, glass, wood, and concrete waste are sent to recycling.

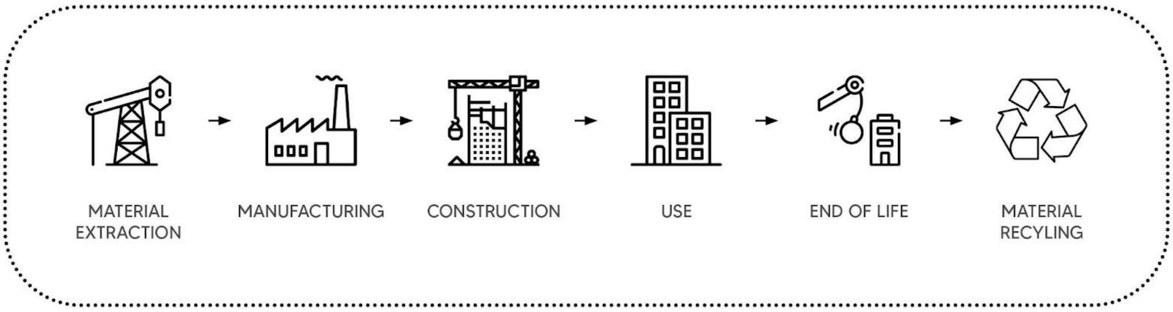

Figure 25: Scenario II Life Cycle Stages

Figure 25 illustrates the life cycle of Scenario II. The considered life cycle stages are explained. For each stage, the contribution of the emissions derived from transportation is also included. As different from Scenario II, materials are sent to the recycling process at the end of the life cycle of the building. Possible recyclable materials are wood, glass, and concrete. The emissions derived from the recycling activities and impacts of transportation are also included in the calculations for this scenario.

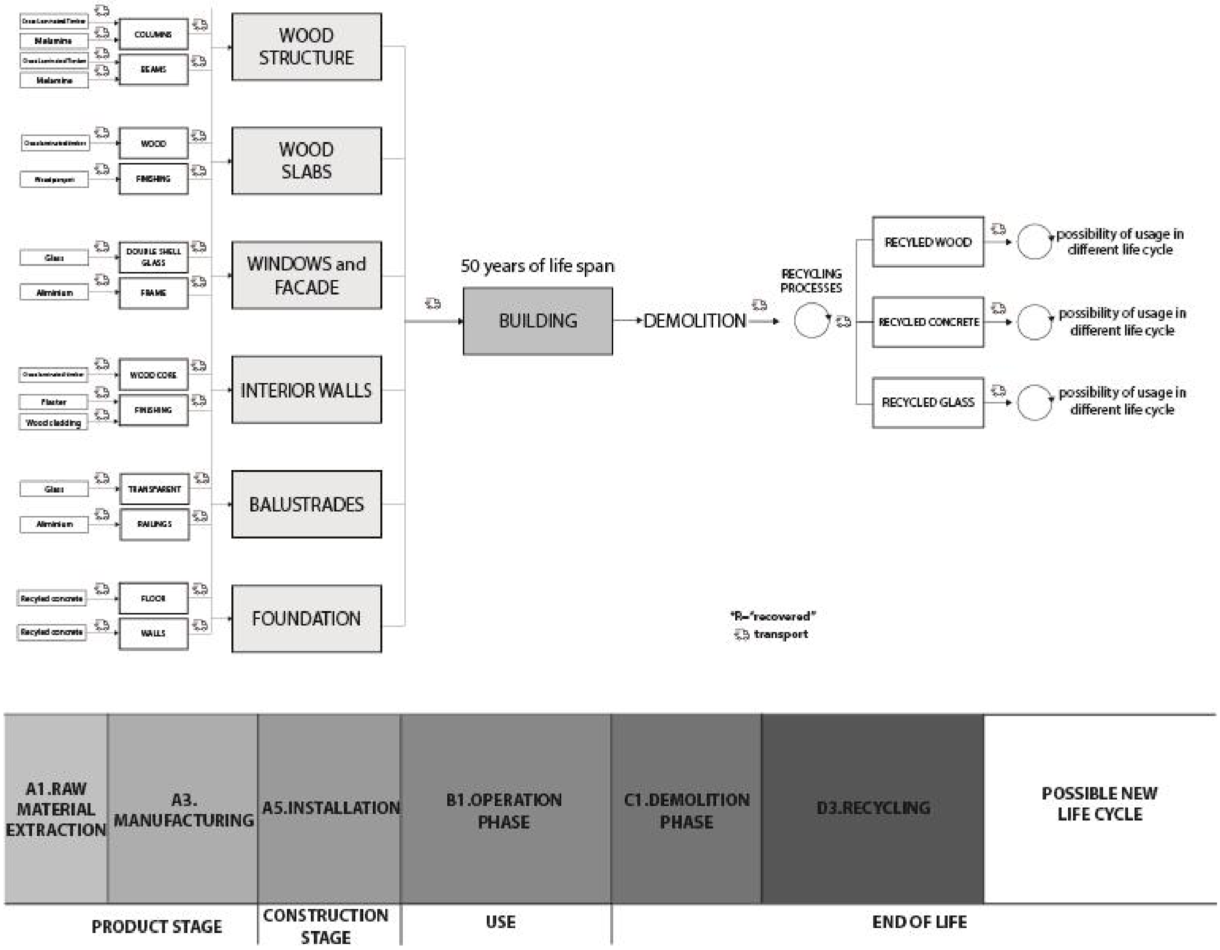

Figure 26: Simplified flowchart of Scenario II

Table 11 shows the Life Cycle Inventory (LCI) of Scenario II to perform the impact assessment. Quantity data for the Life Cycle Inventory is provided by the designers and 3D computer models. Whereas the data regarding the specific activities like production flows are derived from the literature review.

Scenario	Parts	Life Cycle Stage	Material	Description	Amount	Unit	ELCD Database
SCENARIO II	STRUCTURAL ELEMENTS	A1,A3	Glulam	Pinewood	3.43532 1E7	kg	Pine wood, production mix, at saw mill, timber, 40% water content - DE
		A3		Heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	30000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	SLABS	A1,A3	Slabs	Pinewood	14317.0	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Beams	Pinewood	725	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	FACADE ELEMENTS	A1,A3	Aluminium	Aluminium production	908	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	906	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	WALLS	A2	Wall Structure	Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A2		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A1,A2		Pine wood	2022	kg	Pine wood, production mix, at saw mill, timber, 40% water content - DE
		A2		Water	500	kg	Dummy_Water for industrial use
		A1,A2	Plaster	CaSO4	300	kg	Gypsum plaster (CaSO4 alpha hemihydrates), production mix, at plant, via calcination of calcium sulphate dihydrate, grinded and purified product - DE
		A2		water	500	kg	Dummy_Water for industrial use
	BALUSTRADES	A1,A3	Aluminium	Aluminium production	67.5	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	70	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	2000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	1500	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BASEMENT	A1,A3	Pre-Cast Concrete	Pre-cast concrete	300	kg	Pre-cast concrete, production mix, at plant, minimum reinforcement, concrete type C20/25, without consideration of casings - RER
		A2		Transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BUILDING OPERATION*	B6	Domestic Use	electricity	200000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		B1		Biodegradable waste	-2000	kg	Landfill of biodegradable waste, at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
		B1		Municipal waste	- 200000	kg	Landfill of municipal solid waste, BE, DK technology mix, at landfill site, landfill including landfill gas utilisation and leachate treatment, without collection, transport and pre-treatment - EU-27
		B6		Natural gas	10000	kg	Natural Gas Mix, consumption mix, at consumer, technology mix, onshore and offshore production incl. pipeline and LNG transprt - EU-27
		B7		Water	-10000	kg	Waste water treatment, at waste water treatment plant, domestic waste water according to Directive 91/271/EEC concerning urban waste water treatment - EU-27
	BUILDING CONSTRUCTION*	A5	Constructio n Activities	Different pollutants	250	kg	No provider is available for elementary flows.
		A5		electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A5		heat	50000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27

	A4		Transport(5x)	5*100	T*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	A5		Demolition waste	500	kg	No provider available in the database.
RECYCLING	D3	Recycling Activities	electricity	-300	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
	D3		heat	-906	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
	D3		incineration of glass/inert material	-450	kg	Waste incineration of glass/inert material, at plant, average European waste-to-energy plant, without collection, transport and pre-treatment - EU-27
	D3		incineration of untreated wood	15000	kg	Waste incineration of untreated wood (10,7% water content), at plant, average European waste-to-energy plant, without collection, transport and pre-treatment - EU-27
	D3		incineration of wood products	15000	kg	Waste incineration of wood products (OSB, particle board), at plant, average European waste-to-energy plant, without collection, transport and pre-treatment - EU-27
	C2		transport	-100	kg	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
*For the processes/products which do not exist in the ELCD Database, the closest available process/product is selected.						
* The procedure of end-of-life (EoL) in the OpenLCA software, the Opposite Direction Approach (ODA) is used.						
[1]The distance for the transportation is assumed 100 km for each process.						
*Consumptions in the operation phase are based on assumptions since they do not affect the relative results.						
*Processes in the construction phase are based on assumptions since they do not affect the relative results.						

Table 11: Detailed LCI of Scenario II

4.2.1. Scenario II Results

Impact Category	Unit	Impact Result
Acidification potential	mol H+ eq	1.94504E4
Climate change potential	kg CO2 eq	3.56859E6
Eutrophication (marine) potential	kg N eq	3379.43490
Ozone depletion potential	kg CFC11 eq	0.17267
Photochemical ozone formation potential	kg NMVOC eq	1.12892E4

Table 12: Impact results of Scenario II

Scenario II covers the same life cycle stages as Scenario I, however, at the end of the building life, the waste of glass, wood, and concrete is recycled. Table 12 illustrates the total environmental impacts in 5 selected categories derived from Scenario II. These results address the total impact of the all life cycle stages.

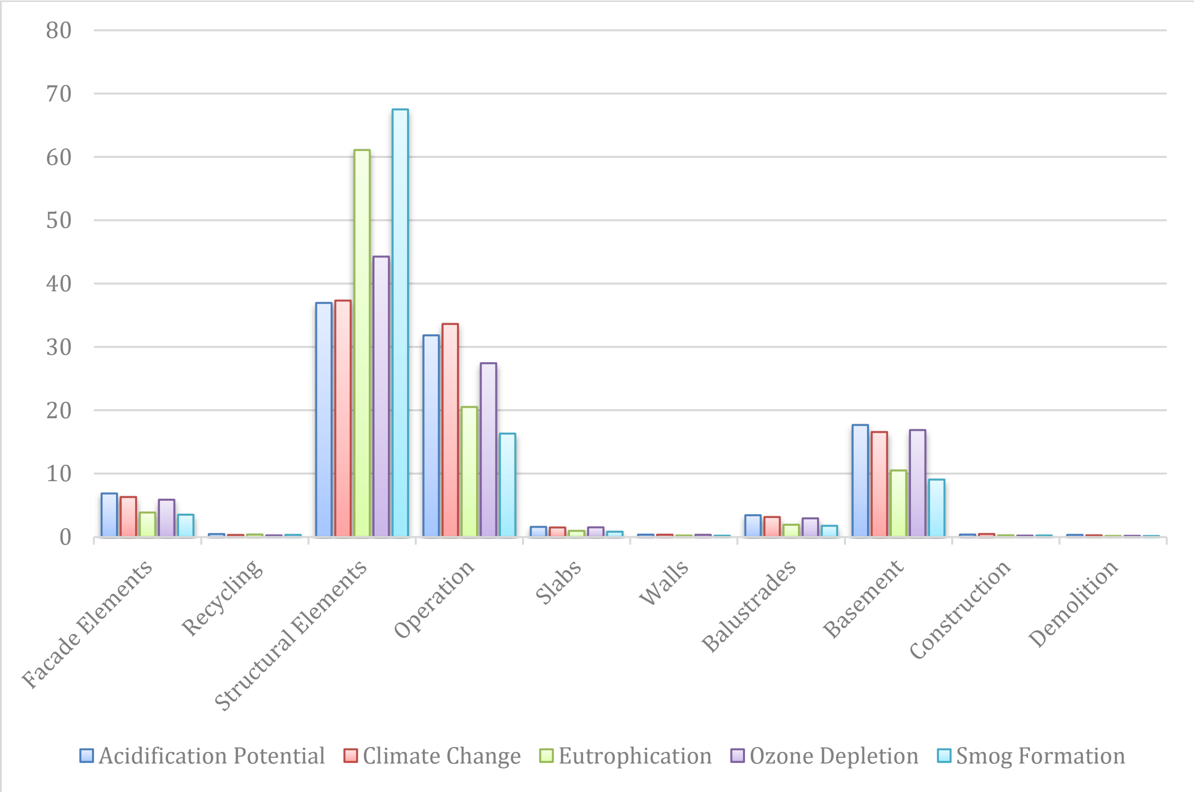

Figure 27: Scenario II contribution of processes chart

4.3. Scenario III

Scenario III is based on circular building components which are possibly disassembled and being used in another life cycle. In this scenario, once the building completed the service life of 50 years, by the activity of disassembly, building components like frames, wood structures, slabs, and windows are ideally recovered and used in another life cycle of a building. In this scenario, possible repair requirements after disassembly are ignored. All the components are considered ready to use at another building.

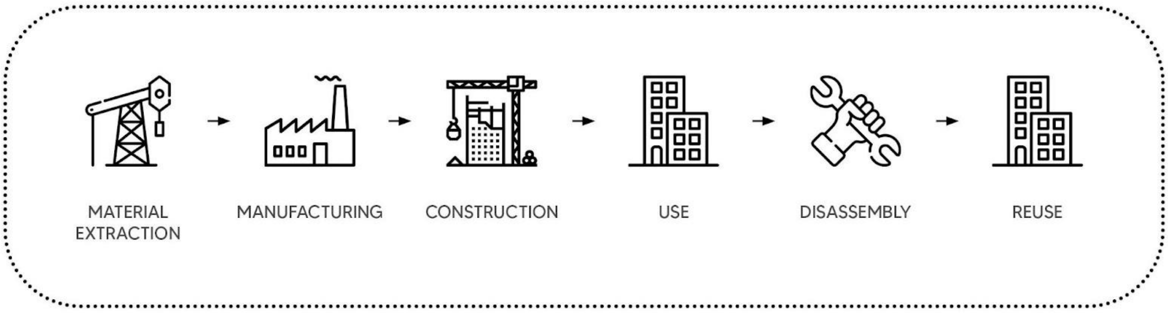

Figure 28: Scenario III Life Cycle Stages

Figure 28 illustrates the life cycle of Scenario III. The considered life cycle stages are explained. For each stage, the contribution of the emissions derived from transportation is also included. As different from Scenario I and Scenario II, the third scenario slows and closes the loops thanks to the combination of circular design strategies. Each building component (slabs, structural elements, façade elements, etc.) designed to be disassembled and to be reused. In this way, once this particular building completes its lifespan of 50 years, the aforementioned building components are considered reusable in different buildings. Therefore, the initial emissions and impacts derived from the manufacturing of those parts are avoided in the calculations.

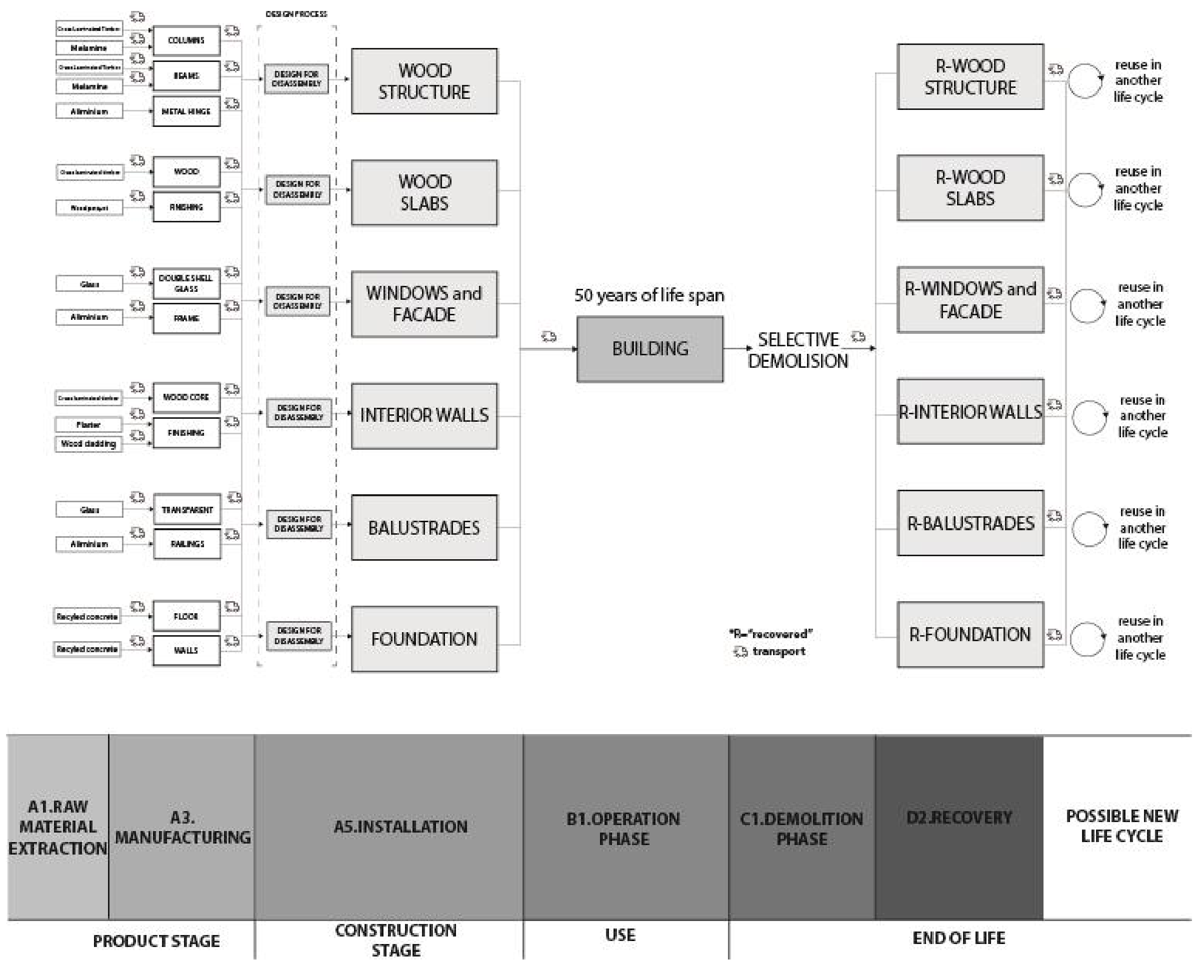

Figure 29: Simplified flowchart of Scenario III

Table 13 shows the Life Cycle Inventory (LCI) data of Scenario III required for the impact assessment. Quantity data for the Life Cycle Inventory is provided by the designers and 3D computer models. Whereas the data regarding specific activities like production flows are derived from the literature review.

Scenario	Parts	Life Cycle Stage	Material	Description	Amount	Unit	ELCD Database
SCENARIO III	STRUCTURAL ELEMENTS	A1,A3	Glulam	Pinewood	3.43532 1E7	kg	Pine wood, production mix, at saw mill, timber, 40% water content - DE
		A2		Heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	30000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	SLABS	A1,A3	Slabs	Pinewood	14317.0	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Beams	Pinewood	725	kg	Pinewood, production mix, at saw mill, timber, 40% water content - DE
		A3		heat	3000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A3		electricity	10000	MJ	Electricity from hydro power, production mix, at power plant, AC, 230V - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	FACADE ELEMENTS	A1,A3	Aluminum	Aluminum production	908	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	906	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	WALLS	A2	Wall Structure	Electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A2		heat	10000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A1,A2		Pine wood	2022	kg	Pine wood, production mix, at saw mill, timber, 40% water content - DE
		A2		Water	500	kg	Dummy_Water for industrial use
		A1,A2	Plaster	$CaSO_4$	300	kg	Gypsum plaster ($CaSO_4$ alpha hemihydrates), production mix, at plant, via calcination of calcium sulphate dihydrate, grinded and purified product - DE
		A2		water	500	kg	Dummy_Water for industrial use
	BALUSTRADES	A1,A3	Aluminum	Aluminum production	67.5	kg	Aluminium sheet, production mix, at plant, primary production, aluminium semi-finished sheet product, including primary production, transformation and recycling - RER
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
		A1,A3	Glass	Glass production	70	kg	Container glass (delivered to the end user of the contained product, reuse rate: 7%), production mix at plant, technology mix - RER
		A3		Electricity	2000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		A3		heat	1500	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
		A2		transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BASEMENT	A1,A3	Pre-Cast Concrete	Pre-cast concrete	300	kg	Pre-cast concrete, production mix, at plant, minimum reinforcement, concrete type C20/25, without consideration of casings - RER
		A2		Transport	1*100	t*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	BUILDING OPERATION*	B6	Domestic Use	electricity	200000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
		B1		Biodegradable waste	-2000	kg	Landfill of biodegradable waste, at landfill site, landfill including landfill gas utilisation and leachate treatment and without collection, transport and pre-treatment - EU-27
		B1		Municipal waste	-200000	kg	Landfill of municipal solid waste, BE, DK technology mix, at landfill site, landfill including landfill gas utilisation and leachate treatment, without collection, transport and pre-treatment - EU-27
		B6		Natural gas	10000	kg	Natural Gas Mix, consumption mix, at consumer, technology mix, onshore and offshore production incl. pipeline and LNG transprt - EU-27
		B7		Water	-10000	kg	Waste water treatment, at waste water treatment plant, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment - EU-27
	BUILDING CONSTRUCTION*	A5	Constructi on Activities	Different pollutants	250	kg	No provider available in the database.
		A5		electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR

	A5		heat	50000	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
	A4		Transport(5x)	5*100	T*km	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER
	A5		Demolition waste	500	kg	No provider available in the database.
DISASSEMBLY	C1	Deconstruction Activities	electricity	10000	MJ	Electricity grid mix 1kV-60kV, consumption mix, at consumer, AC, 1kV - 60kV - GR
	C1		heat	300	MJ	Heat, consumption mix, at consumer, residential heating systems from wood pellets, boiler, max. heat output 14,9 kW, at a temperature level of 70°C - EU-27
	C2		transport	1*100	kg	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payload - RER

*For the processes/products which do not exist in the ELCD Database, the closest available process/product is selected.

* The procedure of end-of-life (EoL) in the OpenLCA software, the Opposite Direction Approach (ODA) is used.

[1]The distance for the transportation is assumed 100 km for each process.

*Consumptions in the operation phase are based on assumptions since they do not affect the relative results.

*Processes in the construction phase are based on assumptions since they do not affect the relative results.

Table 13: Detailed LCI of Scenario III

4.3.1. Scenario III Results

Impact Category	Unit	Impact Result
Acidification potential	mol H+ eq	6937.61826
Climate change potential	kg CO2 eq	1.33487E6
Eutrophication (marine) potential	kg N eq	770.72812
Ozone depletion potential	kg CFC11 eq	0.05311
Photochemical ozone formation potential	kg NMVOC eq	2061.45473

Table 14: Impact results of Scenario II

Scenario III applies the circularity principles and uses circular building components. Building components such as structural elements, façade elements, walls, slabs, and pre-cast concrete blocks for the basement, are assumed to be re-used in another building once the 50 years lifespan is completed. Therefore, the impacts derived from the initial production of those components are ignored. Table 14 illustrates the total environmental impacts in five selected categories derived from Scenario II. These results address the total impact of the all life cycle stages.

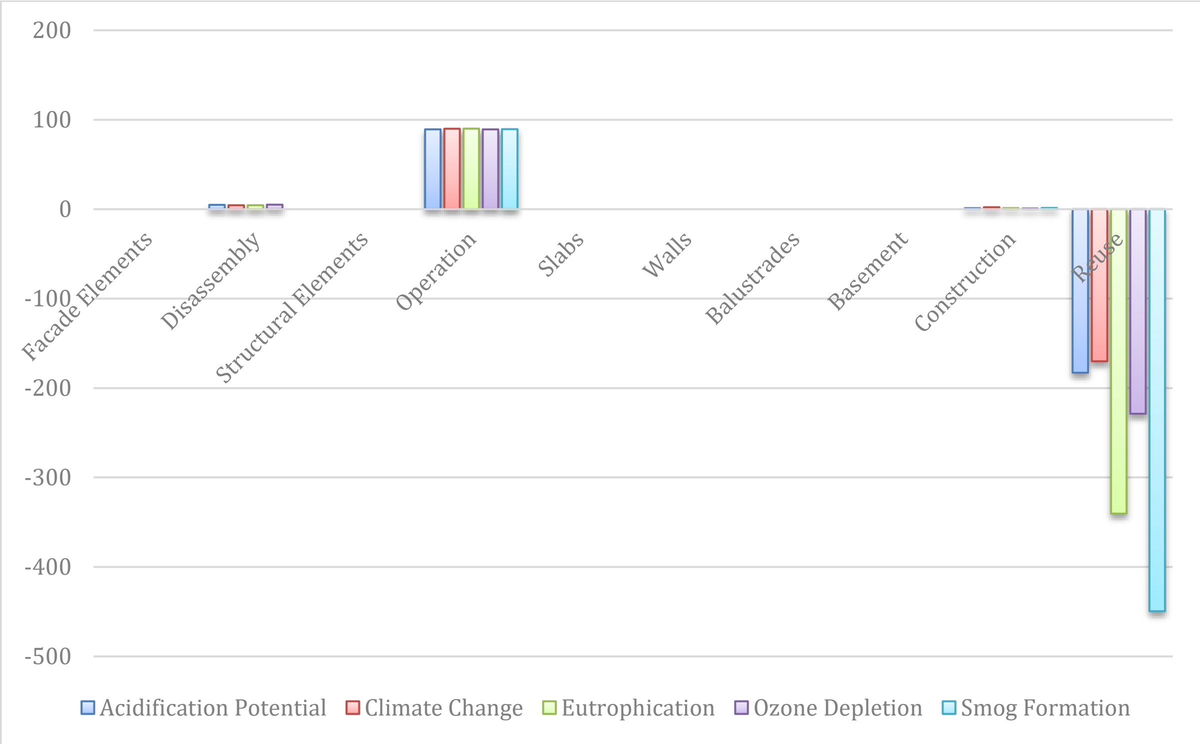

Figure 30: Scenario III contribution of processes chart

4.4. Comparison of Results

Impact Category	Unit	Scenario I	Scenario II	Scenario III
Acidification	mol H+ eq	1.25819E5	1.94504E4	6937.61826
Climate change	kg CO2 eq	2.80329E7	3.56859E6	1.33487E6
Eutrophication	kg N eq	1.74156E4	3379.43490	770.72812
Ozone depletion	kg CFC11 eq	1.06505	0.17267	0.05311
Smog Formation	kg NMVOC eq	4.43276E4	1.12892E4	2061.45473

Table 15: Relative results of three scenarios

Table 15 illustrates the comparison of the Life Cycle Impact Assessment of three scenarios in 5 selected categories. The results above represent the environmental impacts derived from the same building with 50 years lifespan but with different end-of-life scenarios.

The following chart indicates the relative indicator results of the three life cycle scenarios. For each indicator, the maximum result is set to 100% and the results of the other variants are displayed in relation to this result.

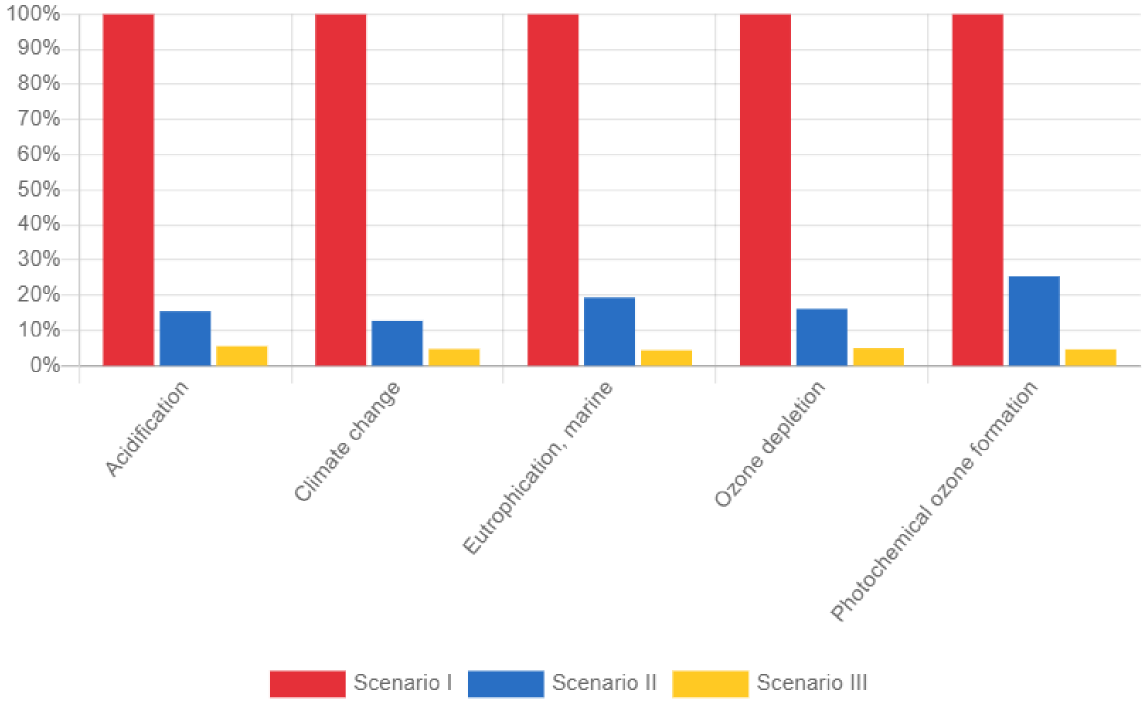

Figure 31: Relative results of the scenarios

As demonstrated in Figure 31, total environmental impacts derived from Scenario I is the highest, Scenario II follows and Scenario III has the lowest impact among the scenarios. Business as usual practices in the building industry as represented in scenario I result in a high environmental burden. Circularity principles such as recycling as illustrated in the second scenario could help to reduce the total impact of the building. Whereas in the third scenario, reuse of the components can help to minimize the total impacts due to lack of initial extraction and manufacturing emissions. Table 16 demonstrates the contribution of impacts by each scenario.

		Acidification potential	Climate change potential	Eutrophication (marine) potential	Ozone depletion potential	Photochemical ozone formation potential
SCENARIO I	**RAW MATERIAL AND PRODUCTION STAGE**					
	Structural Elements	5,71%	4,75%	11,86%	7,18%	17,19%
	Façade Elements	1,06%	0,80%	0,75%	0,96%	0,90%
	Slabs	0,25%	0,19%	0,19%	0,25%	0,21%
	Walls	0,06%	0,05%	0,05%	0,06%	0,05%
	Balustrade	0,53%	0,40%	0,38%	0,48%	0,45%
	Basement	2,73%	2,11%	2,04%	2,74%	2,31%
	CONSTRUCTION STAGE	0,06%	0,06%	0,05%	0,04%	0,06%
	OPERATION STAGE	4,92%	4,28%	3,98%	4,55%	4,16%
	END OF LIFE STAGE					
	Demolition of the building	0,05%	0,03%	0,03%	0,03%	0,04%
	Disposal	84,61%	87,31	80,67%	83,83%	74,62%
SCENARIO II	**RAW MATERIAL AND PRODUCTION STAGE**					
	Structural Elements	36,96%	37,33%	61,10%	44,27%	67,51%
	Façade Elements	6,88%	6,32%	3,87%	5,89%	3,53%
	Slabs	1,60%	1,51%	0,97%	1,53%	0,84%
	Walls	0,38%	0,37%	0,24%	0,35%	0,21%
	Balustrade	3,44%	3,16%	1,94%	2,95%	1,77%
	Basement	17,69%	16,58%	10,51%	16,89%	9,07%
	CONSTRUCTION STAGE	0,39%	0,48%	0,27%	0,23%	0,25%
	OPERATION STAGE	31,84%	33,64%	20,53%	27,44%	16,33%
	END OF LIFE STAGE					
	Demolition of the building	0,34%	0,27%	0,17%	0,19%	0,16%
	Recycling activities	0,47%	0,33%	0,40%	0,26%	0,34%
SCENARIO III	**RAW MATERIAL AND PRODUCTION STAGE**					
	Structural Elements	0%	0%	0%	0%	0%
	Façade Elements	0%	0%	0%	0%	0%
	Slabs	0%	0%	0%	0%	0%
	Walls	0%	0%	0%	0%	0%
	Balustrade	0%	0%	0%	0%	0%
	Basement	0%	0%	0%	0%	0%
	CONSTRUCTION STAGE	1,10%	1,29%	1,17%	0,74%	1,36%
	OPERATION STAGE	89,27%	89,94%	90%	89,21%	89,44%
	END OF LIFE STAGE					
	Disassembly of the building	4,82%	4,38%	4,41%	5,02%	4,60%
	New Life Cycle	-182,9%	-170,9%	-340,37	-228,68%	-449,52%

Table 16: Contribution of impacts for scenarios

CHAPTER 5: CONCLUSION

5.1. Key Findings

Building and construction industry is a key factor in to fight against climate change. Buildings have a great impact on the environment throughout it is whole life cycle. Activities related to the building's life cycle contribute the greenhouse gas emissions and resource depletion and they generate a serious amount of waste. The actors in the industry should take a step to reduce the environmental impacts.

The main focus of the linear economy has been economic profit. The ''take-make-dispose'' mentality has been resulting the depletion of our resources and generates a serious amount of waste. On the contrary, the circular economy proposes a system where the loops in production are closed through reuse, recycling, and refurbishment. Those principles can be adapted to any business sector which has a high environmental burden. The impact derived from building and construction-related activities can be quantified with many tools. Life Cycle Assessment (LCA) has been one of the most useful assessment tools to quantify the environmental impacts of products and/or systems.

This study aimed to implement a Life Cycle Assessment (LCA) in an administrative building based on three life cycle scenarios. The main objective of this study was to compare and quantify the business-as-usual building life cycle and the one with circularity principles adopted. To do so, three life cycle scenarios were investigated by using cradle to grave approach. The results of the life cycle assessment are presented in five impact categories, acidification potential, climate change potential, smog formation potential, eutrophication potential, and ozone depletion potential.

Scenario I included raw material extraction, manufacturing, construction, operation, demolition, and disposal. Scenario II included raw material extraction, manufacturing, construction, operation, demolition, and by expanding the system boundary materials recycling. Whereas Scenario III, after completion of the ordinary life cycle stages which are raw material extraction, manufacturing, construction, operation, and demolition adapted the circular building components principles and the possible re-use of the building components are considered in the calculations.

The findings of this study addressed that, business-as-usual building concludes their life cycle with the highest environmental burden. The environmental impact derived from the activities included in Scenario I resulted in the highest environmental impact in all of the five impact categories.

The highest contributor to the total impact of this scenario appeared to be the generated waste and its landfilling activities. The highest contribution to the global warming potential (GWP), with a percentage of 87,31% is the disposal activities.

Scenario II examined a similar building life cycle. However, as an end-of-life treatment, building waste is not disposed of yet recycled. The impact results indicated that scenario II performed better than the first one in all five impact categories. Environmental impacts derived from the building could reduce by recycling the used materials. The highest contributor to the total impact in this scenario was the raw material extraction and the manufacturing of structural elements. The operation stage followed.

Scenario III, with the difference between Scenario I and II, examined the possible reuse of components at the end of the life cycle. Prior to the construction, during the design phase, the building parts are considered to be designed circular. Therefore, once the completion of life cycle, building components such as wooden structures, façade elements, slabs, and so on are recovered and used as the input of the new life cycle of a building. In this way, the initial emissions and impacts from the manufacturing of the components were avoided. Scenario III performed the best among all scenarios. Expanding the life cycle of the components by reusing them helped to obtain the lowest impacts among all scenarios. Even better than recycling, the reuse of the building component reduced the impacts on every category by up to 50%.

A literature review that was conducted before this study showed that activities belonging to the building and construction industry cause resource depletion and high emissions of CO2. According to the findings of this study, implementation of the circular economy principles in the building sector can reduce the total environmental impact of the buildings. Recycle, and reuse can be adapted in the building sector with the aim of impact reduction and resource depletion. Possibly, circular buildings can help to build circular cities. Circular built environments can be achieved through the circularity principles where the buildings are building parts designed to be recycled or reused. In this way, the total waste of building activities may be reduced. Other than that, the initial emissions for the raw material extraction and manufacturing processes can be decreased through circular buildings.

Life Cycle Assessment can be implemented in the design process to quantify possible emissions and impacts of the building. It can perform as a decision-making tool in the design processes. Since the possible environmental burdens are quantified with LCA methodology, it can be used in design choices, material selection, and so on. It is helpful for decision-makers, architects, designers, and investors.

5.2. Limitations

This study addressed the quantification of environmental impacts through the alternation of end-of-life scenarios. The results of this study could be beneficial to the LCA methodology, construction, and manufacturing industry. This study was carried out by using a free database. Therefore, the data related to construction and materialization activities were quite limited.

On the other hand, this study used a hypothetical case study, which was still in the design phase. Therefore, the material data is very limited and mostly calculated on assumptions.

Another limitation of this study was the maintenance and repair activities during the operational phase of the building's life cycle are not taken into account since building and/or business owners may differ in their approach and frequency to maintenance and repair activities.

5.3. Future Developments

As mentioned in the previous chapter, this study was carried out with limited data. With the alternation of end-of-life scenarios, the total environmental impacts are compared by using the Life Cycle Assessment method. This study can serve as a source for future studies with a more precise and detailed case study project. The BIM model was not used for this study, but for detailed material and construction data, this study can be augmented with a BIM model.

Moreover, due to the limitations of free databases, this study utilized limited construction data. More precise results can be obtained by using a more advanced database.

The scope of this study was limited to assessing the circularity of some building components. For future researchers, the concept of reusing components and their environmental benefits hold great potential.

Although only end-of-life scenarios are emphasized in this study, the operational phase is also an important factor of environmental impact. Similar studies can be implemented to this case study building only focusing on the operational phase.

This study used the Life Cycle Assessment method to quantify the environmental impacts of the buildings. However, the concept of sustainability is not limited to the environment. There are also economic and social aspects that need to be addressed as well as environmental impacts. For a more holistic life cycle analysis, social and economic indicators should be taken into account for further studies.

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