Master Thesis

Proposal of a demolition and disassembly methodology for old buildings in order to maximize the material recovery potential based on the LCA results

the case study of the Leek municipal workshop building, Westerkwartier in Groningen, Netherlands

Tara Bahari

Aug 2021

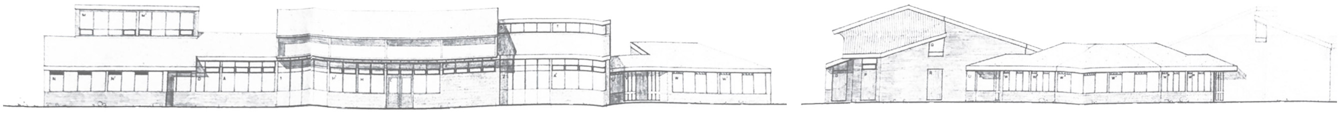

Figure 1 Leek Municipal Workshop building, front view perspective. Antea Group, 2019.

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Master Thesis

Faculty of REAP
Resource Efficiency in Architecture & Planning

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In co-operation with:

Municipality of Westerkwartier, Groningen, the Netherlands

Submitted on:

16 August 2021

DECLARATION OF AUTHORSHIP

Hereby I declare that I have written the current master thesis by myself, without any help from others and without the use of documents and materials other than what is specified in the relevant section of this document. I have mentioned all used sources and cited them correctly according to established academic citation rules.

The intellectual work presented in this research thesis has been carried out by the use of One Click LCA software, as the processor of the input information that has been mainly provided by the Municipality of Westerkwartier. Various literature have been reviewed and benefited from for different sections of this research. All sources have been specified in the relevant parts. I did not seek any advice from any external consultant.

Furthermore, I confirm that this research thesis has been exempted from any direct or indirect monetary benefit from any third party. Also, it has not been submitted for any other program or qualification anywhere before and is being presented originally as the completion of the REAP master degree at HafenCity University of Hamburg.

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HCU university, even though I missed the opportunity of being much accommodated in its rooms due to the restrictions caused by the pandemic situation, provided me with wonderful online support. I would like to thank the staff at the student services and the REAP department for their wonderful support and care.

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A kind appreciation to my family too, for sharing thoughtful ideas and being always there patiently during my stressful days of completing this project.

OUTLINE

The investigation of this thesis would aim to measure the environmental performance of materials throughout their lifecycle in an old municipal building, with a public function, by evaluating various environmental impact indicators and the embodied carbon in the materials the building consists of, followed by a proposal of potential ways to reuse or recycle the materials once they reach their end of operational life.

The objective is to maximize the resource efficiency of the building after destruction and reconstruction, by utilizing the recycled materials in the new construction. It would eventually shift the urban district towards having a more beneficial environmental footprint, through the footprint enhancement and material recycling of the individual buildings that form it. The focused building is a forty six years old one that needs to be demolished and rebuilt, within the reformation plan of an urban quarter in Westerkwartier district in Groningen, Netherlands.

The scope of the thesis is defined by the study of this building in the aforementioned district, as an integrated part of a project under development. The project consists of fifteen buildings, under the authority of the local municipality in Westerkwartier, calling for ideas and solutions in order to reach social, functional and environmental sustainability as well as climate neutrality of the buildings in question, eventually by 2030. The buildings are originally planned to be approached in three different methods, according to their condition; considering some have to be just renovated and some have to be demolished and rebuilt. Also some buildings will be designed and built from scratch. Any proposal or research provided to the project, has to conform to European norms on sustainability and preferably focus on the use of materials, according to a local authority. The construction phase of the project is foreseen to be started in two to five years from the date of this paper.

The author believes that the outcome of this master thesis would be beneficial for awareness raising of the project planners and the decision makers on site as well as the design team engaged in it, towards the conception of sustainable solutions for the urban context in Westerkwartier, Groningen. This will include a proposal of potential demolition methods to extend the reuse of the materials and their potential energy, based on the LCA results and reviewing various literature on the building demolition and destruction.

In the end, it will be tried to examine the worthiness of revitalizing the old building materials during or after the demolition and the effectiveness of it on achieving the main goal of the project, which is reaching energy neutral buildings, in the reformed district of Westerkwartier by 2030. The results could serve as a basis for further development of the project, suggesting to perfrom a quality control criteria when materials can be safely reused and when not.

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LIST OF ABBREVIATIONS

LCA Life Cycle Assessmet
EOL End of Life
IEA International Energy Agency
CO^2 Carbon Dioxide
SDS Sustainable Development Scenario
ISO International Organization for Standardization
BREEM Building Research Establishment Environmental Assessment Method
GRI Global Reporting Initiative
DGNB Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
CDW Construction and Demolition Waste
GDP Gross Domestic Product
DFD Design for Disassembly
DFA Design for Adaptability
C2C Cradle to Cradle
EPEA Environmental Protection Encouragement Agency
IEE Initial Embodied Energy
REE Recurrent Embodied Energy
DEE Demolition Embodied Energy
kWh Kilowatt Hours
KG Kilogram
EPD Environmental Product Declaration
NL the Netherlands
PEX Cross-Linked Polyethylene
Alu Aluminum
PVC Polyvinyl Chloride
GFA Gross Floor Area
GWP Global Warming Potential
AP Acidification Potential
EP Eutrophication Potential
ODP Ozone Depletion Potential
POCP Photochemical Ozone Creation Potential
GER Gross Energy Requirement
LCIA Life Cycle Impact Assessment
CO^2e Carbon Dioxide Equivalent
SO^2e Sulfur Dioxide Equivalent
PO^4e Phosphate Equivalent
$CFC_{11}e$ Trichlorofluoromethane Equivalent
MJ Mega Jules
LCI Life Cycle Inventory
BAMB Buildings as Material Banks

1. INTRODUCTION

1.1 OBJECTIVES AND SCOPE

Building sector, as a huge contributor to the global energy consumption, over one-third of global final energy consumption and around 40% of total direct and indirect CO^2 emissions, according to IEA, bears a great responsibility in cutting down its environmental impacts (IEA, 2020). Energy demand from buildings and construction works keeps rising, and reached its highest point in 2019, as a result of improved energy access in developing countries, spread use of energy extensive devices, and rapid growth in global buildings floor area. The IEA Sustainable Development Scenario (SDS), thus, addresses the development a major transformation in the global energy system to be achieved by various means in different sectors by 2030 (IEA, 2020). Figure 4 displays the evolution of different regions in energy intensity before and after the Sustainable Development Scenario.

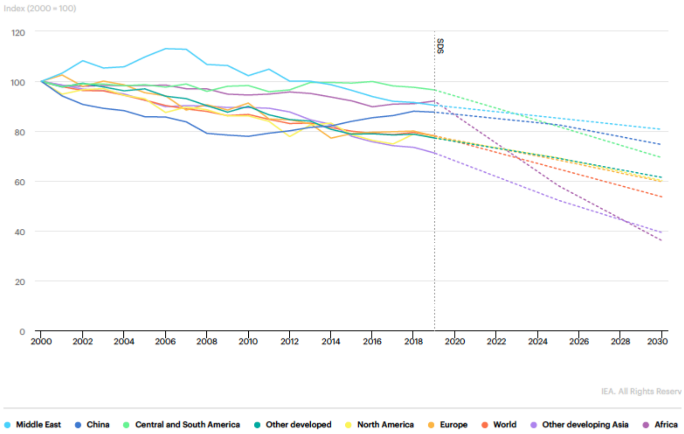


Figure 4 Buildings sector energy intensity in selected regions in the Sustainable Development Scenario, 2000-2030, IEA, 2020.

Accordingly, making buildings with fewer impacts is an important goal to be achieved in the building sector. Energy, as one of the most predominant resources in this sector, is crucially discussed, and because of that, any technologies to produce low energy buildings are in the limelight of the researches and studies (Thormark, C., 2002).

Furthermore, many municipalities in various cities around the world, attempt to deal with the issue of construction waste after demolishing the buildings. Avoiding and reducing the waste generation in the building sector on one hand, and examining the methods how to revive the demolition waste into useful building materials suitable for reuse on the other hand, are the major endeavors that the authorities and developers go through. Buildings are known to have the largest life cycle impacts during their functioning life or the use phase. However, recently, understanding the environmental impacts such as pollution and emission potential, energy consumption, and the use of natural resources in the buildings construction have gained a lot of value (Blengini, 2009).

The current research thesis attempts to analyze an old building with public function, within the authorship of the Groningen municipality, with the means of life cycle assessment in order to achieve the following objectives:

- Find out the relative contribution of building materials to the pre-use environmental impacts
- Categorize the building materials based on their criticalness and identify the hotspots

- Indicate the building materials with feasibility for recycling or reuse
- Evaluate the end-of-life impacts when reuse , recycling or downcycling replaces landfilling
- Assess end-of-life material recovery opportunities and propose demolition methodology

The research scope defines modelling the building in a LCA software, to evaluate the relevant environmental impacts as well as the potential building circularity that follows an introduction to the principals of circular economy and Cradle to Cradle concepts in the building sector. At last, the results of the analysis are synthesized and possiblr demolition methods are discussed, to find the most appropriate one.

Evaluating the environmental impacts of buildings and construction processes using LCA has been considered in the construction sector for over 20 years. With the help of LCA, the environmental impacts in different categories are quantified for each life cycle stage of the building. The LCA process is supported by the standards of ISO 14000 series, ISO 21930 and 21931 for construction products. Besides that, the European standards of EN 15804 and EN 15978 have been adopted to harmonize the LCA approaches in Europe, respectively for product level assessments, and for building level assessments (Lowres & Hobbs, 2017).

1.2 RESEARCH QUESTIONS

The question pursued in this research is as following:

- What can be an optimum methodology for demolition and/or disassembly of an old, public building in order to maximize the material recovery potential?

It attempts as well, to find an answer to the question of:

- How can the life cycle assessment affect the decision making process of demolishing and rebuilding such buildings?

The following keywords can be retrieved in this paper:

Circular economy in demolition, material life cycle assessment, construction and demolition waste, reuse of materials, deconstruction

1.3 THE WESTERKWARTIER MUNICIPALITY

The development project of the Westerkwartier Municipality of Groningen was set up in 2019 with an objective of proposing well-founded and well-considered solutions for municipal buildings of the future (Gemeente Westerkwartier, 2021). The main objectives that are to be pursued in this project, known as Future-Proof Housing, as indicated by the Research Report April 2021, include but are not limited to the following:

- Promotion and administration of connections between residents, partners and institutions
- Development of sustainable buildings which are suitable for future concepts of working such as working from home, consultation, collaboration and meeting with residents, entrepreneurs, education, research and innovation developments. This section would also be inspired by experiences gained during the Corona time.
- Appropriate design to ensure spatially correctness and completeness of the buildings that are in balance with the environment

(Gemeente Westerkwartier, 2021).

The project consists of various buildings including four town halls, eight field service workshops and three other municipal buildings, which are all in poor maintenance condition and among those, there are major concerns on the municipal yards of Leek and Marum. The buildings are not only in need of substantial maintenance, but also do require attention on their sustainability performance which is currently totally low. The project has therefore, raised investments for renovation and maintenance works to be carried out in a ten years perspective (Gemeente Westerkwartier, 2021).

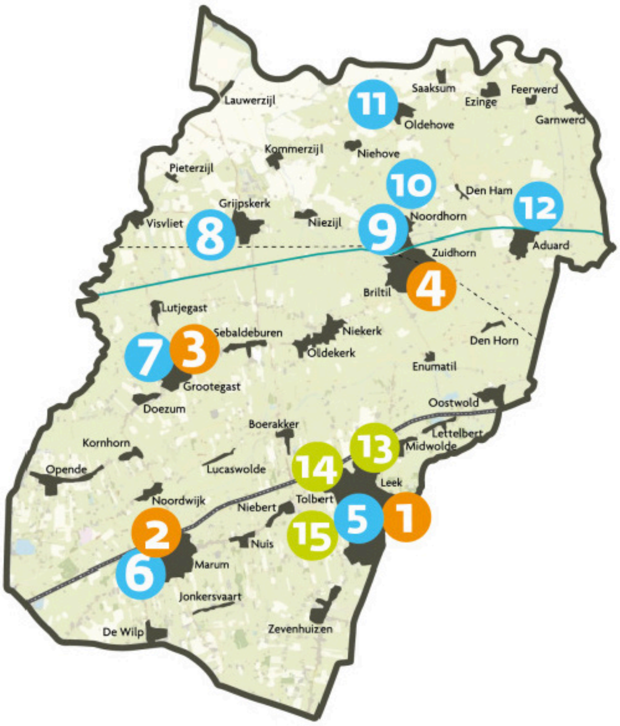


Figure 5 Current locations of the Future-Proof Project, Municipality of Westerkwartier, Groningen, NL, Gemeente Westerkwartier, 2021.

However, the municipality of Westerkwartier states in their Research Report on April 2021, that the investment amount would not meet a very high CO^2 emissions reduction, as according to the project plan, only approximately 60% of the emissions would be reduced through the current buildings. The entire CO^2 emissions of the fifteen buildings that are under the project's concern, amounts to 1300 tons per year and is estimated to be reduced to 500 tons by the means of the current plan; but still not acceptable to meet the sustainability goals. It should also be borne in mind that many of the obsolete buildings on site, do not provide an opportunity for long-term execution of any plan for further sustainability, due to their limitation of use or noticeably poor condition (Gemeente Westerkwartier, 2021).

Hence, the local authorities tend to seek advice and consultation from experts in the field of sustainability, in order to maximize the performance of the project.

In order to fulfill the topic of this thesis, the author considered the two highly concerned and poor quality buildings of this project, which are as stated earlier, the municipal yards of Marum and Leek. The public workshop of the latter, Leek, has been then selected as the case study of this research thesis. According to the building pathology report and the maintenance requirements of the selected building, as provided by the local authorities, the Leek Municipal Workshop is in poor condition and nominated to be demolished and later rebuilt within the frameworks of the project.

It is assumed that the outcome of this research thesis would benefit the project developers in understanding the materials that the building consists of, in terms of their contribution to the environmental impacts and the embodied carbon in them, as well as potential end-of-life scenarios that would be executable on site in order to enhance the material recovery after demolition.

2. METHODOLOGY

2.1 SYNTHESIS

The current research thesis studies the environmental impacts of building materials during their pre-use and end-of-life stages, while taking a glance at the principles of the circular economy and Cradle to Cradle concepts. Studying such principles, from the author's point of view, would prepare the reader with a summary of guiding information on the importance of these principles in moving towards a more environmentally and economically sustainable future in the world of building and construction. Therefore, a brief overview of these primary, yet preparatory concepts are provided in the following sections of this paper, that precedes the most extensive part of the research which is the life cycle assessment of the building for different environmental impact indicators.

As a case study, it engages a 46 year old building from the properties under authority of the Westerkwartier Municipality in Groningen, Netherlands. Hence, it provides supplementary input from a material recycling and sustainability perspective to the urban regeneration project of Westerkwartier (refer to 1-3), followed by a proposal of demolition/disassembly methodology based on the analysis results.

The research has been carried out in two steps. Firstly, the building under study was modelled in detail in a life cycle assessment software (refer to 2.2), based on the data and figures provided by the Westerkwartier's project leading team. The supplied dataset represented the actual properties of the building, including the materials and components, as well as quality condition and deficiency of the materials. Moreover, building plans, including floor plans, sections and elevations were delivered timely during the research. The outcome of the LCA arranges a holistic view of the environmental and energetic performance of the building and the materials it consists of. Thus, it was adopted as the main tool for the analysis stage.

Secondly, a set of literature was looked into that reviewed the environmental impacts caused by buildings during their life cycle, rubble recycling as well as demolition and disassembly solutions. The results of the study were then contrasted and adapted to the various demolition and deconstruction methods introduced by the literature and a methodology was synthetized in the end, that would match most appropriately with the actual situation of the building under study and aims to shift towards sustainability.

A site visit to the building could unfortunately not take place, since the current Covid-19 situation imposed some limitations to health and travelling conditions. Nevertheless, video conferences and written correspondence with the local counselor, Mr. Aartjan Feijstma, and the project leader, Mr. Reinier Antonides were carried out at organized intervals.

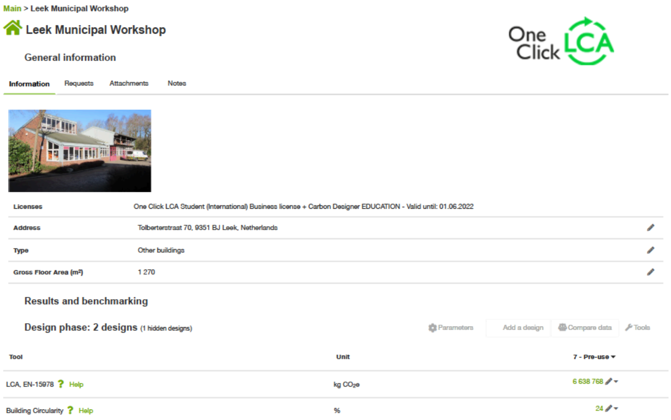
2.2 SOFTWARE

One Click LCA software has been taken as the main software for life cycle assessment in this research. The author used the official student license of the software that offers the following calculations tools for the study:

- **Life-cycle assessment, EN-15978:** Building life-cycle assessment according to the European Standard EN 15978. This covers life cycle stages from cradle to grave with separate reporting to product stage, construction process, use stage, operational energy, and end of life. The software and related datasets are compliant with ISO 14040/14044 or EN 15804. It is compliant with the Active House Specification requirements.

- **Building Circularity:** Material efficiency and circular economy for BREEAM MAT 06 and GRI G4 reporting as well as other purposes.

(One Click LCA, 2015.)



Licenses	One Click LCA Student (International) Business license + Carbon Designer EDUCATION - Valid until: 01.06.2022
Address	Tolberterstraat 70, 9351 BJ Leek, Netherlands
Type	Other buildings
Gross Floor Area (m²)	1 270

Design phase: 2 designs (1 hidden designs)

Tool	Unit	7 - Pre-use
LCA, EN-15978	kg CO₂e	6 638 768
Building Circularity	%	24

Figure 6 Home page view of the project modelled by author in One Click LCA, One Click LCA, 2021.

The material-locked end of life scenario is the recommended method by One Click LCA module. The scenario calculates the C1 and C2 based on the default values that exist for demolition and transportation. However, not every certification tool includes C1 and C2 emissions in their scope, and in most of the cases, C1 emissions consider only the fuel consumption of the required machinery and C2 emissions are based on the removed material mass. The scenario also addresses the C3, C4 and D emissions. The relevant calculations are made based on EN 15 978 / EN 15804 and follows the categorization and end-of-life scenarios from DGNB International, 2014, pg. 21. (One Click LCA, 2015).

The end-of-life stages as defined in the material-locked scenario by One Click LCA is presented in table 2.1.

C1	De-construction, demolition
C2	Transport to waste processing
C3	Waste processing for reuse, recycle and/or recycling
C4	Waste Disposal
D	Reuse, recovery and/or recycling potentials, expressed as net impacts and benefits

Table 1 Definition of emission groups addressed by material-locked E-O-L scenario, One Click LCA, 2015.

Though, it was attempted to adjust the EOL scenarios later for each material or component, rather than keeping the material-locked presets. Accordingly, the LCA results were updated. The customized EOL scenario for each material is presented in table 5 section 4.6.

3. PRINCIPLES

3.1 CIRCULAR ECONOMY MODEL

The fast growing, volatile economy across the globe, imposes noticeable resource depletion and energy crisis. This has urged a need to fundamental changes in the economic systems, so as to improve the resource efficiency and economical performance. Thus, methods to reuse and recycle the materials, products or components as much as possible are constantly being developed to help restoration of energy and material input in the industries. To pursue this objective, the conservative, linear economy shall be replaced with a circular one that eliminates the direct disposal of materials and brings them back into the lifecycle (Ellen MacArthur Foundation, 2013).

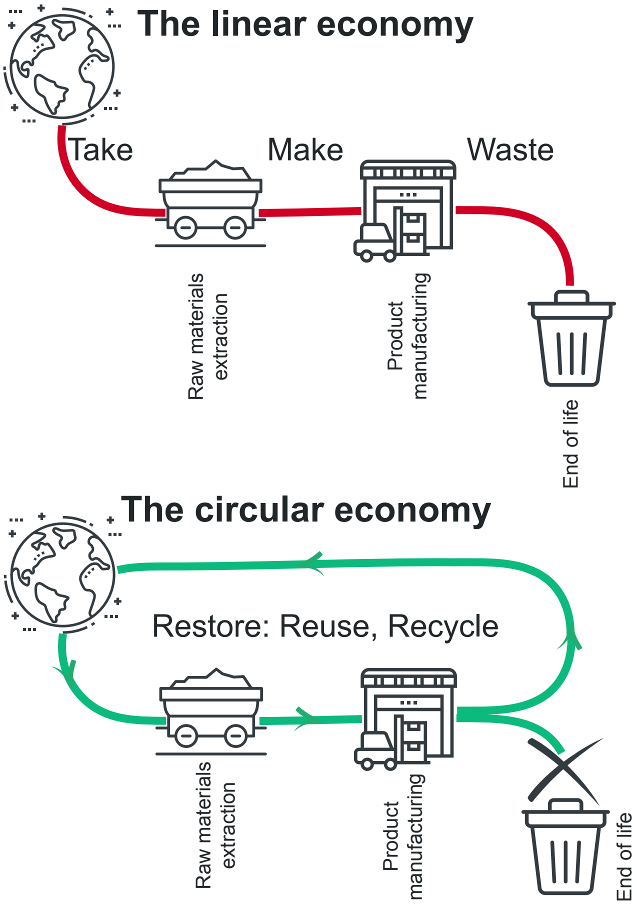


Figure 7 The Linear Economy vs Circular Economy. Data retrieved from talkintrashwithuhn.com, 2017 and Desso-ce, graph regenerated by author, 2021, Icons from thenounproject.com.

The linear economy is based on a consumption model and comprises of a “take-make-dispose” pattern which brings about an entire resource loss after the products have been consumed during their service life, without being restored or recycled (Ellen MacArthur Foundation, 2013).

The circular economy, on the other hand, operates on the basis of restoration and regeneration. The novel economic model, as introduced by Ellen McArthur Foundation, replaces the material’s “End-of-Life” concept with restoration, incorporates the use of renewable energies, and wipes out the materials with toxic compounds that hinder the reuse. Furthermore, the final generated waste and pollution would be decreased as a result of maximized reuse and minimized disposal of materials (Ellen MacArthur Foundation, 2013).

A building or a product in circular economy, can have several, even hundreds or thousands of suppliers, while it is not the same in linear economy. Circular Economy aims to transform the role of suppliers, to engage and involve them at the front end to encourage circular innovation while make saving. As a result, there will be an interaction between customers and suppliers. On the contrary, in conservative linear economy, suppliers remain at the back end, being behind the development process that ends in consequences such as:

- Low incentives for suppliers to evolve with the circular innovation

- Lesser involvement in the enhancements of the systems
- Delivery of low quality products with weak performance

(Mulhall, D. et al., 2019)

Induced by the principles of the Circular Economy and the Cradle to Cradle concept, many project developers in various businesses, including building and construction sector tend to reset their project goals towards reaching less negative or even positive impacts, caused by the buildings. Setting of the goals could take place in different stages of the project, from planning to operation; though determining which stage to take and which positive impact to anticipate, is a remarkable challenge (Mulhall, D. et al., 2019).

Efficiency could be maximized while the negative footprints get minimized, thanks to the transitional policies that many companies are now utilizing, in order to shift from conventional, linear economy to the circular one. Sustainability should no longer be only an “add-on” to the companies and industries, but it should be integrated in the operative and executive systems towards making positive impacts on the environment while eliminating the negative ones. Hence, the credible, innovative and circular decisions of the businesses, either in building sector or any other industry, largely influence the society and the environment (EPEA, 2020).

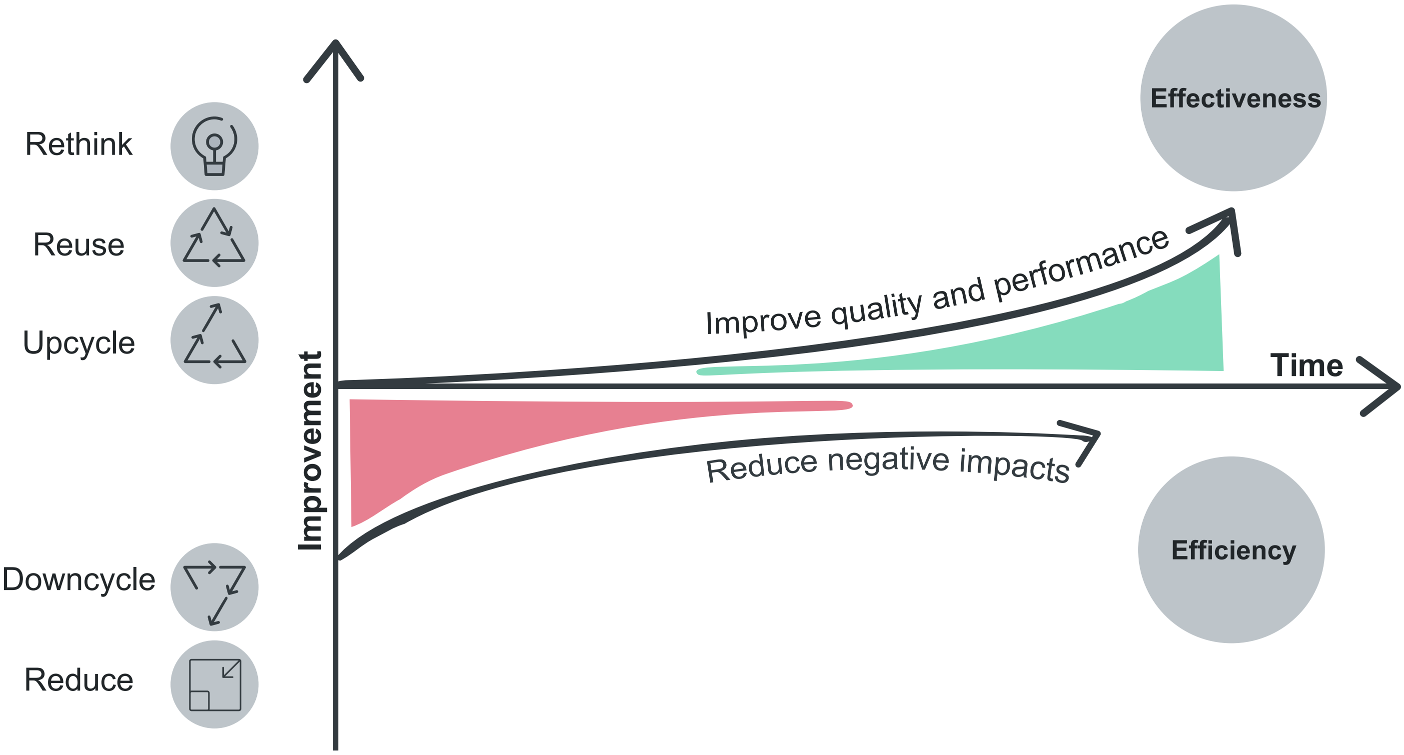


Figure 8 Upcycle Chart; The Journey from traditional sustainability to C2C-inspired circularity. Data retrieved from Design principle for Beneficial Companies, EPEA, 2020 and Mulhall, D. et al., 2019, graph regenerated by author, 2021, Icons from thenounproject.com.

The building sector, due to its enormous impacts on the environment, is a predominant industry in which the circular economy can be implemented.

Traditional environmental methods have always been attempting to reduce the negative impacts of buildings on the environment. Thanks to the guidelines of the Circular Economy, not only the negative footprints of the buildings would be eliminated, but also would the buildings leave positive impacts on the environment. This means, buildings can reach a healthy environmental footprint, which adds value and quality by offering a range of benefits. In other words, a building with healthy footprint is beyond being green or passive; it brings added value for the stakeholders by:

- Enhancing the qualities of materials, energy and life in economic, social and ecological aspects
- Providing a continuous improvement in all phases of the building project, from planning until disassembly and recycling
- Prompting healthy amplitude rather than just minimizing the negative impacts
- Taking an adaptive approach to the existing procedures, without forcing new formalities, regulation or certification
- Having a universal climate adaptability to dominant climate regimes, from extreme, hot and tropical, to moderate ones.

(Mulhall, D. et al., 2019)

3.2 CIRCULAR ECONOMY IN CONSTRUCTION AND DEMOLITION

The huge share of building industry in generating waste across different cities worldwide, has dragged a lot of attention from municipalities towards the management of construction and demolition waste (CDW). As reported by López Ruiz et al., 2020 through Eurostat, the building and construction sector accounted for 6.2% of world GDP, 6.3% in Europe and 5.7% in Latin America as of the year 2016. This reflects the remarkable size of the industry in economy; However, the environmental impacts caused by the sector is in parallel relatively enormous. Also, the largest waste stream worldwide belongs to construction sector, accounting for 36%, 67% and around 40% of the total solid waste generated in 2016 in the European Union, the United States and China, respectively (López Ruiz et al., 2020).

The term of construction waste refers to all the solid debris that is resulted in the construction site after the partial or full demolition of buildings, structures, roads, etc. The main constituents of the CDW are glass, plastics, wood, steel, mortars, concrete and bricks, as well as excavated soil (Noor et al., 2020). Exact quantification of CDW amounts is not simple, though it is estimated to account for around 30% of the total weight of the building materials that are initially delivered to the construction site (Osmani, 2011).

Inappropriate management of this waste stream, leads to many negative impacts on the environment relevant to the extraction of raw materials and manufacturing of building elements, besides saturating the landfills. In addition, waste treatment in construction industry is quite important, since a proper treatment can result in sustainability of material production and supply as well as reduction of energy consumption (Noor et al., 2020).

Following the concept of circular economy in demolition procedures as well as waste management strategies, brings about numerous advantages. When a building reaches the end of its useful operational life, circular economy attempts to replace the linear process of material termination, by bringing them back to the life cycle through reuse and recycle (Ginga et al., 2020). Instead of a “take, make, consume, dispose” pattern as taken up by linear models, circular economy proposes improved building strategies that concentrate on CDW reduction and management, that would not only reduce environmental impacts, but also result in economic growth. It initiates regenerative models aiming to optimize the efficient use of materials, to maintain their value and end up in less CDW during the entire life cycle of the building (López Ruiz et al., 2020).

In the circular model, waste is considered to be a new source of materials and hence disposal should be avoided as much as possible. According to this, the circular economy in construction and building industry comprises of a “material recovery and production” phase, after its other four stages of preconstruction, construction and building renovation, collection and distribution, and end-of-life (Ginga et al., 2020).

Recognizing the material reuse and recycling potential to reduce the negative environmental impacts which the construction and demolition causes, is principal goal of circular economy in this industry. Its goal is to eliminate and reduce, when elimination not possible, the amount of generated CDW ending up in landfills or being incinerated, as well as enhancing the reuse and recycling quality, as end of life concepts of old buildings, and maximize integrating them into new constructions (Ginga et al., 2020).

However, there is still lack of adequate research and development on a holistic application of circular economy principles on construction and demolition and the majority of current researches concentrate on CDW management and material recovery, within the principles of circular economy. This is not enough though, and circular thinking must be integrated in multiple life stages of buildings (López Ruiz et al., 2020).

An integrated circular economy in construction and demolition industry, according to López Ruiz et al., 2020, should reflect in the five predominant, influencing life cycle stages of a building.

- **Preconstruction:** waste minimization and efficient use of materials through adopting alternative design strategies, circular planning and management

- **Construction and building renovation:** improved site waste management plans to minimize material wastage and waste generation during construction process

- **Collection and distribution:** enhancement of collection and segregation techniques as well as transportation processes. This includes proper collection and sorting at source, e.g. sorting per material type, separating contaminated materials, etc. and leads to enhanced material recovery

- **End-of-life:** maximizing material recovery potential through selective deconstruction and/or pre-deconstruction/demolition audits.

- **Material recovery and production:** recirculation of recovered materials in the lifecycle with the objective of reducing the need for virgin materials

(López Ruiz et al., 2020).

3.3 CRADLE TO CRADLE CONCEPT

The C2C Design Protocol operates at different levels of:

- Philosophy: as an inspirational guide representing the favorable role of human being
- Principles: as frameworks of defining quality and application tools
- Tools: as innovative and applicable means for achieving the measurable quality or goal

The material flows in buildings comprise of products which are planned to be biological nutrients for the biosphere and technical supplements for the Technosphere. The materials value chain in the Circular Economy is defined by the materials cycle proposed by the C2C (Mulhall, D. et al., 2019).

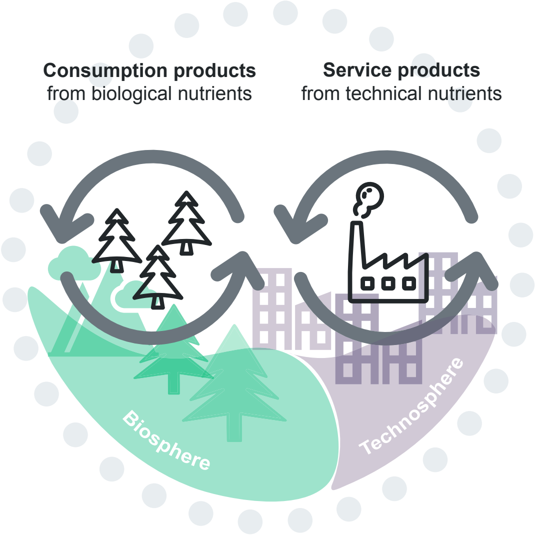


Figure 9 The basis for materials flows in buildings. Products designed as biological nutrients for the Biosphere, and as technical nutrients for the Technosphere. Data retrieved from Mulhall, D. et al., 2019 and EPEA, graph regenerated by author, 2021, Icons from thenounproject.com.

Provided considering the Circular Economy as the new driving system which takes control of the built environment, the Cradle to Cradle concept acts as the steering wheel of the system, providing it with the required guidance. The Chinese legislative bodies on the environment, have been using the term Circular Economy since many years ago. However, it comes to more of a global popularity, thanks to the attempts made by Ellen MacArthur Foundation in 2011 and 2012, as well as the management consultancy carried out by McKinsey & Partners, coupled with editorial support from EPEA, published Towards the Circular Economy, Editions I & II at the World Economic Forum in Davos Switzerland. A third report, as explained by Mulhall, et al., 2019, was published by the World Economic Forum in 2014, followed by even more. “Those reports are driving an international movement to adopt the Circular Economy in business.” There currently exist various definitions for the Circular Economy, making the meaning of the concept comprehensible in different ways; though a general description remains as: “A Circular Economy is one that is restorative and regenerative by design.” Nevertheless, a set of principles, guidelines and methods to pursuit the general concept of the Circular Economy, is defined by the Cradle to Cradle, and hence, here is the linkage between the two concepts (Mulhall, D. et al., 2019).

Here below is the definition of Cradle to Cradle principle, as introduced by the Ellen Macarthur Foundation and McKinsey and Partners in Towards the Circular Economy II, 2013:

> *…The Circular Economy requires careful management of material flows, which are of two*

> *types. These are characterised by McDonough and Braungart in Cradle to Cradle: Remaking the Way We Make Things as biological nutrient and technical nutrients… Biological 'nutrients' are designed to re-enter the biosphere safely for decomposition to become valuable feedstock for a new cycle. Technical 'nutrients' are materials that either do not degrade easily or cause contamination within the biological nutrient flow. These are designed by intention to retain embedded quality and energy.*

If the projects of the construction sector would be designed with a Cradle to Cradle approach, there will be more of positive effects on the environment and human health. In fact, the Cradle to Cradle design broadens the horizons for sustainability and health, in a way that the materials used in buildings can be restored and reused without losing their value and the there are no waste produced (McDonough & Braungart, 2003).

Reuse requires less effort and proceedings compared to recycling, therefore should be a priority over recycling (Hobbs & Adams BRE, 2017). In order to approach this solution, architects and engineers need to consider an optimized selection of high performance materials with low impact on environment and deploy proper components and technologies to reach a more efficient use of resources (Andrade & Bragança, 2017). Buildings erected with materials of high reusability potential result in less dependency on virgin materials. This means that the restored materials and elements of a building can be disassembled and transformed into a bank of material to be used in other buildings, while maintaining the value and generating less waste (Durmisevic et al, 2017). Although apart from the requisitions that architects should consider in the design phase, there should be a devotion in management and cooperation between supplying and recycling companies, for the former to provide material specifications and guide to rematerialization and for the latter to accept the return of used materials, disassemble and restore them for further use (McDonough & Braungart, 2003).

The Venlo City hall in Netherlands can be a proper example in this regard which brought long term cost benefits for the project, in terms of material selection and energy use efficiency. Accoring to MacArthur foundation, the Venlo City Hall project design, structure and furniture focuses on reusablity of materials and diassembly potential with the objective of maintaining sustainablity and recovering financial investment up to some extent. The materials in this building come along with a documented passport including the material components and disassembly procedure guide. So the redisuals of it can be studied in a comprehensive log as a bank of material for further reuse. In addition, adhesive materials are avoided in this project in order to ensure material health and ease the restoration process. Along with the productivity and efficiency of this building, the project expects to recover a 12.5% of investment within the next 20 years (MacArthur Foundation, 2019).

3.4 EMBODIED ENERGY

The embodied energy or the embodied carbon terms refer to the cumulative energy consumed and the emissions released by materials during the entire life cycle of the building. The building life cycle constitutes of all of the various life stages the materials go through, from extraction of and processing of the raw materials to the construction, operation and end of life. However, the emissions and energy consumptions attributed to the operation stage are principally separate from that of the other life stages (Souza, 2020).

Different literature represent the embodied energy in various ways, depending on which stage of the building's life cycle they refer to. The definitions mostly take the embodied energy from a cradle to gate point of view into consideration that encompasses the sum of energy consumed during the pre-construction phase of the building; from extraction of the raw material to manufacturing of the product and transporting it to the construction site, in other words. Besides that, there are other literature that define the embodied energy in an extended perspective of cradle to site, which includes the construction phase as well as the pre-construction and the relevant transportations (Azari, 2019).

From a cradle to grave perspective, as Azari, 2019 explains, the embodied energy perimeter would include the preconstruction and construction phases, as well as the maintenance, demolition disposal phase of a building's life cycle. This definition constitutes of the total energy that is consumed in the entire life cycle of the building, but excludes the operational phase (Azari, 2019).

Taffese & Abegaz describe the main three categories of the embodied energy in buildings as following:

1. Initial embodied energy (IEE): the pre-use phase, that implicates the energy consumed through extraction of raw materials, processing of natural resources, manufacturing of products and transportation to the construction site. The energy used in construction activities is also included in this category.
2. Recurrent embodied energy (REE): the use phase, that implicates the energy consumed during maintenance, repairing and renovation of the buildings during their service life; the occupants' building use pattern as well as their maintenance demands, along with the service life of the buildings and the quality of materials and components, affect the levels of energy consumed in this category.
3. Demolition embodied energy (DEE): the end-of-life phase, that implicates the energy consumed for demolition of buildings at the end of their lifecycle, including recycling and/or re-use of some components and disposal of the others, counting the required transportation, landfilling or incineration processes. Due to lack of adequate data, this category of the embodied energy is considered to be highly uncertain and hard to monitor; though it accounts for the smallest

> share in energy use of a building during its lifecycle.

(Taffese & Abegaz, 2019)

Analyzing the amounts of embodied energy and carbon in the building materials is beneficial for the decision makers who aim to reduce the overall energy consumption and create buildings with fewer impacts on the environment (Taffese & Abegaz, 2019). Life Cycle Assessment (LCA), as a quantitative analysis tool, is a standardized method in this regard, that calculates the environmental impacts of buildings, during their entire life cycle. The numerical results that are generated in a LCA study, represent the material's impacts in different categories while providing comparisons between similar materials or components (Souza, 2020).

The population growth and urban sprawl during the recent years has come along with the need to erect more and more buildings that has surged the energy consumption and CO^2 emissions (Taffese & Abegaz, 2019). It is important to mention that the share of embodied energy in buildings has been growing recently, since more research is being carried out to develop buildings with high energy performance during their operational phase. This refers to the increased levels of embodied energy in the materials and components, from raw materials to manufacturing technology, which are designed and produced to create innovative buildings with low or even zero operational energy consumption. Design for durability, reusing and recycling technologies, are thus critical in fluctuating the efficiency for embodied energy. Various studies have been undertaken in this regard; the results mostly consent on the increase of embodied energy versus operational energy as building gets closer to the low and zero energy technologies. This proves that the conventional buildings with no specific or innovative technique, embody lesser energy within their materials and components. Azari, 2019 compiles a couple of results obtained from different studies and demonstrates them in figure 10.

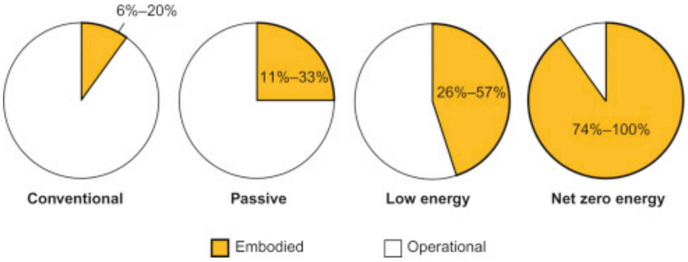


Figure 10 Share of embodied energy in lifecycle energy use of residential buildings with various levels of operational energy efficiency, Azari, 2019.

In addition, the embodied energy in buildings not only varies based on different urban situations in which the building is located, but also deviates according to the type and quantity of the materials that the building comprises of. Buildings made with lightweight materials, for instance, contain smaller amounts of embodied energy, since such materials are in general less energy intensive. Furthermore, cutting down on the transportation distances for material supply to the construction site, reduces the embodied energy through lowering the fuel consumption, which counts in the net energy calculations (Azari, 2019).

4. ANALYSIS

4.1 BUILDING INFORMATION

The present research thesis deals with a municipal public building within the properties of the Westerkwartier municipality in the Netherlands. The building is approximately 46 years old and has an area of 1270 m^2. It is part of the urban renovation plan of the Westerkwartier (refer to 1-3) and is planned to be demolished in the coming couple of years. The details of the building as well as the location map are represented in table 2 and figure 11 respectively.

It lies in a V shape on the site and consists of several workshop salons, various storage rooms, canteen and technical rooms. With a public facility function, the building is operational during 10 working hours for five days per week. According to the building pathology report provided by the Antea Group for the Westerkwartier Municipality, the building is in poor condition and requires fundamental maintenance, if it is to be kept on operating.

Figure 11 Aerial view of the building and its neighboring constructions. Google Maps, 2021.

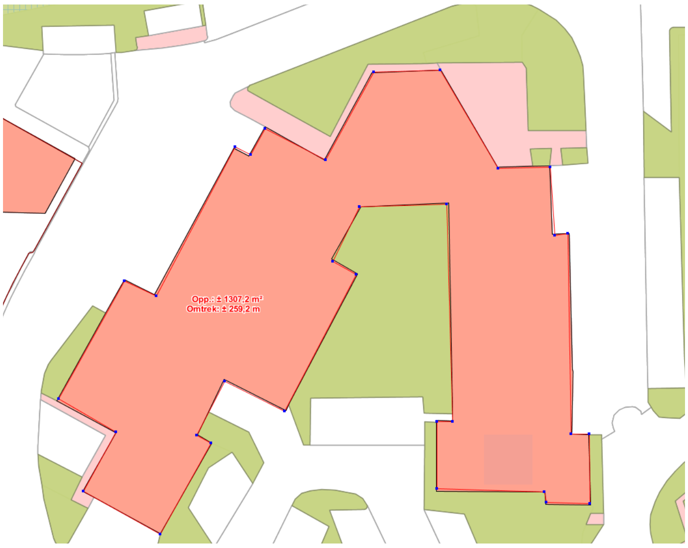


Figure 12 Building territory on site, Westerkwartier Municipality, 2021.

Name	Leek Municipal Workshop (gemeentewerkplaats)	Number of Floors	1,5
Address	Tolberterstraat 70 - 9351BJ Leek	Energy Label	F
Owner	Municipality of Westerkwartier	Fuel Consumption	Natural gas - 40,000 m^3/Y
Type	Public Facility	Power Consumption	35,000 kWh/Y
Function	Meeting, Workshop	Water Consumption	300 m^3/Y
Construction Year	1975	CO^2 Emissions	6,535,808 kilograms per year
Operational Area	1270 m^2	Circularity	28%
Volume	5363 m^3	Current Quality	very poor condition, not maintained

Table 2 Leek Municipal Workshop building information, Westerkwartier Municipality, 2021.

The average annual power consumption is indicated in table 2, though it could fluctuate during different times of the year, due to seasonally different consumption patterns and supply instability (Gemeente Westerkwartier, 2021).

Natural gas is consumed as the main fuel in the building. There are no cooling systems, while a couple of gas boilers generate heat and distribute it through panel radiators into the rooms.

According to the energy scan report carried out by Ecocert group in November 2019, heating accounts for the largest share of energy consumption in the workshop building. The second biggest contributor to the energy consumption is lighting.

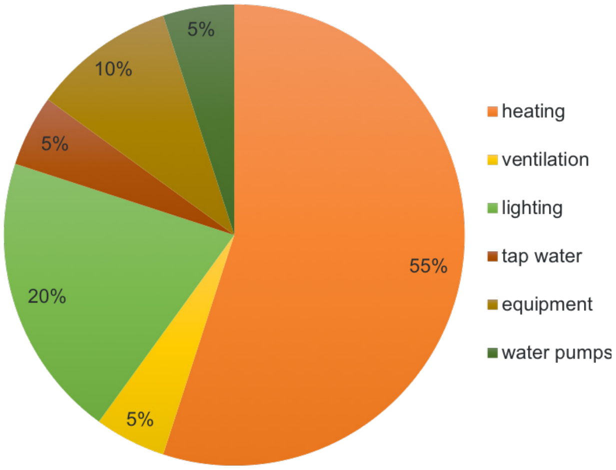


Figure 13 Energy consumption per position, Ecocert, 2019.

Studying the plans and details of the workshop building reveals that it has been built in a typical way with no specific, innovative technology; Although the share of embodied energy in conventional buildings is relatively lower than that of modern, innovative buildings, due to simplicity in the manufacturing of the materials and components that the building constitutes of (Azari, 2019), the workshop building comprises of a noticeable portions of heavy materials such as steel, concrete and masonry bricks. This indicates that a remarkable amount of energy is embodied in the building. Figure 14 shows the classification of predominant materials present in the buildind per mass in kilograms.

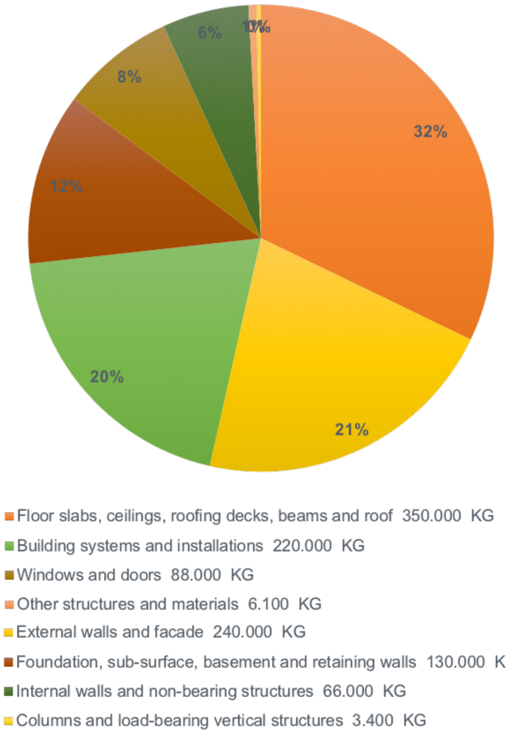


Figure 14 Mass classification of materials constituting the building, One Click LCA, 2015.

4.2 BUILDING STRUCTURE

The main structure of the building consists of steel elements including beams and columns, as well as loead bearing masonry walls. The load bearing system transmits the load to a series of strip foundations, reaching approximately 543 meters long at the depth of 1,05 meters underground. 42 short pillars connect the foundations to the structure system above earth. The entire foundation system composes of reinforced concrete.

Figure 15 Rear view of the building, Ecocert, 2019.

The roofing system is a pitched one with wooden beam and purlin substructure. The interior ceilings are mainly covered with wooden cladding. The walls are from masonry brick with plywood or steel cladding on the exterior and various claddings including stucco, plywood, chipboard or ceramic tiles on the interior side.

The construction of the building dates back to 1975, the post-war period. By the time, in northern areas of Netherlands in particular, the majority of the buildings were constructed with unreinforced masonry. According to a study performed by Jafari et al., 2017, clay bricks, including solid, perforated and frogged units constituted the most of the building masonry materials during the pre-war and post-war times in the Netherlands (Jafari et al., 2017).

Screed cement mortar, natural stone, ceramic tiles, wooden parquets, linoleum and carpet finishes are the materials used in floor claddings in different rooms of the building.

Doors and windows consist of several materials that mainly include hard wood, aluminum and steel frames. Few wooden railings and stairs with steel components are also present in the building.

Figure 16 Interior view of the canteen, Ecocert, 2019.

Numerous fluorescent components supply the lighting of the building. A few halogen and other miscellaneous lightbulbs operate as well.

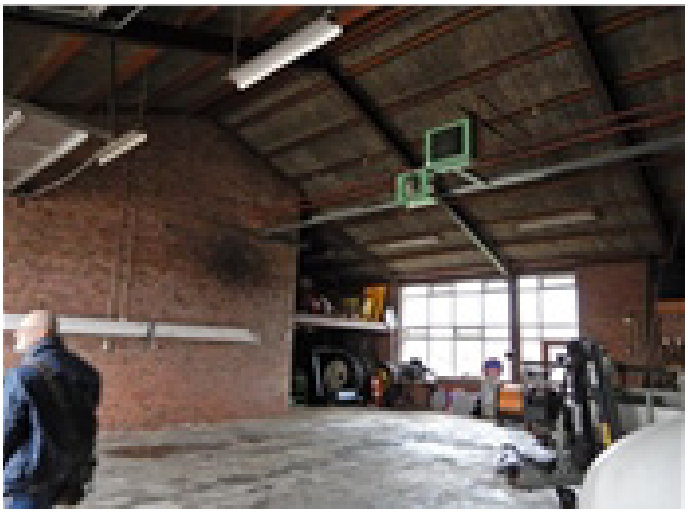


Figure 17 Interior view of the workshops, Syplon Maintenance Plan, 2020. Roof inner structure,f luorescent lamps and other existing equipment are visible in this image.

The air inside the building is replaced through 15 electric ventilation fans. The hot water supply is carried out with a flow-through, directly heated, gas-fired as well as a directly heated electric water heater. The circular pumps and distribution pipes complement the system.

Figure 18 Old water heating equipment currently operating in the building, Syplon Maintenance Plan, 2020.

The pathology report reveals a serious to severe level of deficiency in almost all parts of the building, including all the materials and components. The reported deficiencies mainly include faults such as abrasion, corrosion, crackle, deep cracks, dirt, sediment, discoloration, erosion, weathering, siltation, powdering, defect sealing and wood rot. Other deficiencies such as bare, missing or damaged parts are also existent in numerous components. Moreover, the technical instruments and systems that are currently operating in the building, have exceeded 75% of their theoretical lifespan and hence are required to be replaced immediately (Pathology Report by Antea Group, 2015).

Figure 19 Visible damages on window frames, Syplon Maintenance Plan, 2020.

Figure 20 Poor condition of doors and facade, Syplon Maintenance Plan, 2020.

4.3 SYSTEM BOUNDARIES

The system boundaries under study in this research are the pre-use and end-of-life phases of the building. The LCA model has been generated accordingly. The use-phase have been set out of the scope of this research, nevertheless could provide basis for the future studies on erection of the new building, considering recycling scenarios, reuse of non-virgin materials, and the relevant maintenance requirements and energetic remarks in particular.

The pre-use phase comprises of manufacturing of products and their transportation to the site, as well as the required activities for construction processes.

The use-phase is considered to last 50 years. The building is 46 years old now and is planned to be demolished in the next couple of years. The mentioned life span would include any activities including the use by occupants, as well as maintenance and renovation incidents and incorporate the operation energy consumed over these years for various purposes such as heating, air ventilation, sanitary, hot water supply, lighting, equipment, etc. The use-phase is excluded from the LCA model in this study.

The end-of-life phase takes the demolition of the building into account and comes along with the treatment of the materials after destruction which includes on-site primary processing, preparation for recycling, incineration and disposal of the debris through landfilling, counting the required transportation.

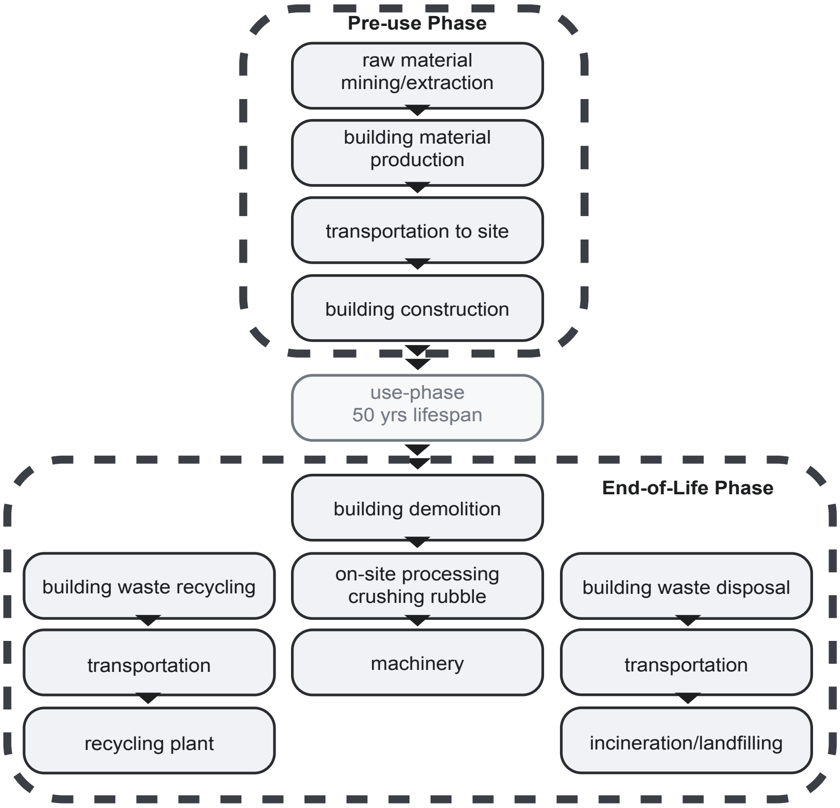


Figure 21 System boundaries used in the LCA model, Author, 2021.

4.4 DATA SOURCES

The data has been gathered from various sources which are summarized in table 3. The inventory data including the quantities of the building materials were mostly determined from the pathology survey conducted by Antea Group in 2015. For the items that were not available in the survey report, an estimation was made based on the original drawings and details of the building. One Click LCA was used as the modelling software, and its databases have been used for different components of the model. The inventory analysis of the specific fixtures of the building, such as electric cables, sanitary valves, heat and water pipes were performed with less precision, due to ambiguity and lack of accurate data. Miscellaneous elements such as tools and equipment used by the workshop occupants, furniture, cooking equipment, cutlery and crockery of the canteen were excluded from the analysis. For the majority of materials, like concrete and steel, the locally produced options were selected from the One Click database. For those with no local supply option, the alternative from the nearest location have been chosen. The figures representing the average annual water, fuel and electricity consumption of the building have been retrieved from the interview with the project team.

Lifecycle Phase	Subsystem	Data Sources
Pre-Use	Building material production	• Inventory data measured by Antea Group, NL for the building pathology study, provided by the project team • Missing quantities estimated based on assumption through provided architectural plans and comparison with neighboring buildings • Masonary brick type defined by the data provided in literature Jafari, et al., 2017 • Piping amount defined by the default local recommendations of the One Click LCA, 2015
	Transportation to site	• Estimated transportation data obtained from One Click LCA, 2015
	Construction on site impacts	• Estimated based on One Click, 2015 construction site scenarios and excavations for European temperate climate zone
	Construction losses / Wastage on site	• Estimated data obtained from One Click LCA, 2015
Use	Use of electricity for heating, fuel, sanitary water, etc	• Data measured by Antea Group, NL for the building pathology study, provided by the project team • Data measured by Ecocert, NL for the building energy scan study, provided by the project team • Data provided by the project team
End-of-Life	Demolition / Deconstruction	• Materials EPD provided by One Click LCA, 2015
	Separation	• Materials EPD provided by One Click LCA, 2015
	On-site recycling	• Materials EPD provided by One Click LCA, 2015
	Transportation	• Materials EPD provided by One Click LCA, 2015

Table 3 Data sources based on subsystems in each lifecycle phase

4.5 INVENTORY ANALYSIS

The workshop building consists of various elements that shape the construction in its load bearing system, outer shell, inner room divisions, interior settings and equipment. The main inventoried materials and components were classified into five major groups, based on their function category in the building. An overview of the inventoried items is represented in figure 22.

Afterwards, the quantities were determined based on the existing sources of information and approximate transportation distances were extracted from the databases integrated with the One Click software. Table 4 summarizes the main inventoried structural elements of the building with their estimated transportation distance.

For the transportation distances for the categories that consist of several elements, the mean transportation distance has been shown in the table, in order to demonstrate an overview. The actual distances for individual elements have been used in the calculations in the LCA model. The equipment existing in the building systems and installations are assumed to be reused,

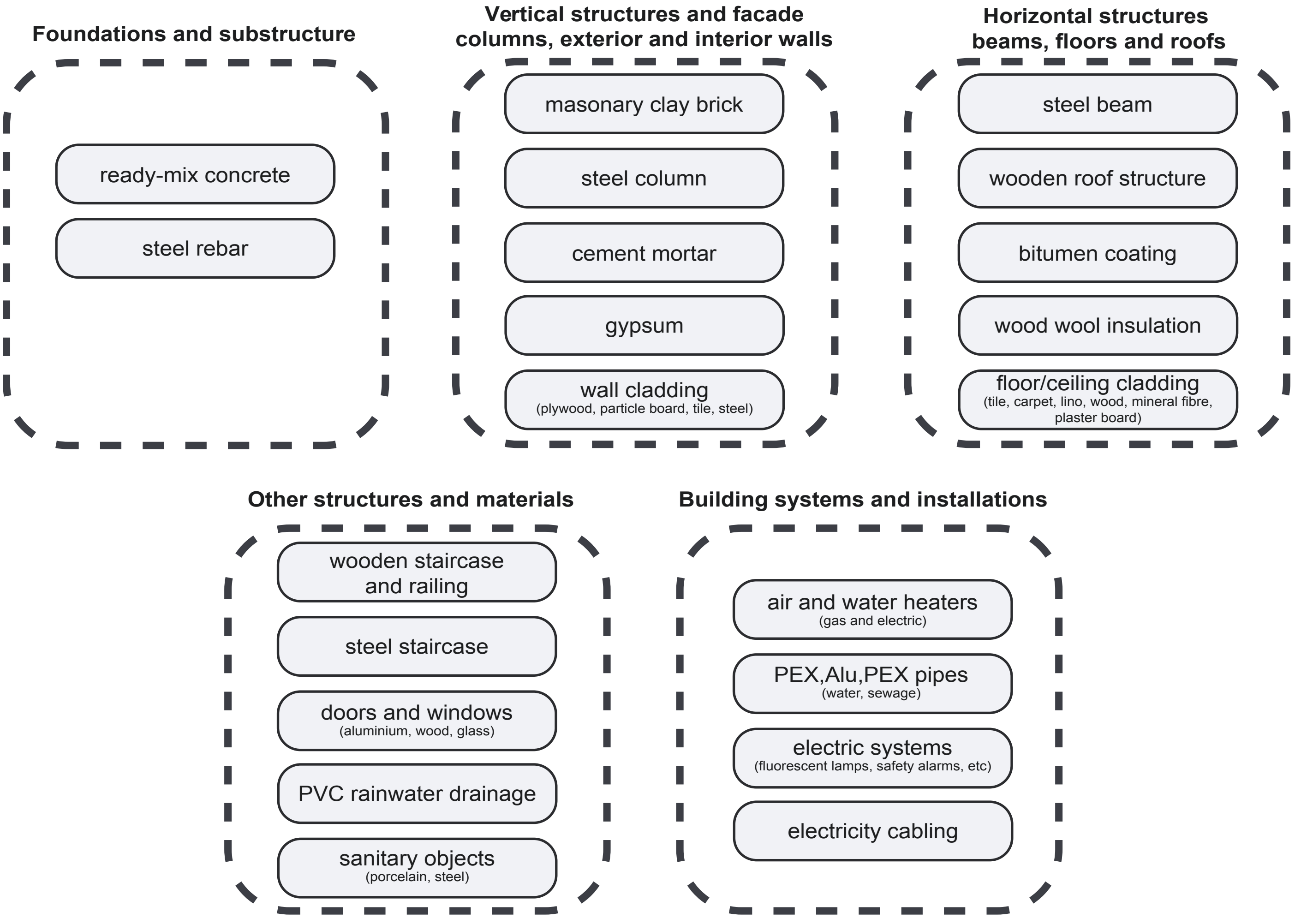


Figure 22 Main material categories inventoried in the LCA model, author, 2021.

without their constituting raw materials be recycled, hence they have been excluded from the main material categorization, as shown in table 4.

A recommended construction site scenario was obtained from One Click LCA, which reflects average site impacts for moderate European climate. Accordingly, assumed average production of construction waste 5 kg/m^2 (GFA) of general construction waste. Assumed electricity use is 37 kWh/m^2 (GFA) and assumed total use of diesel stands for 4.5 l/m^2 (GFA) (One Click LCA, 2015). For the excavation works, a volume of 133.350.0 m^3 was estimated based on the available foundation drawings. The obtained excavation scenario, following the One Click LCA, consists of removal of mass with a density of 1.760.0 kg/m^3 perfomed with machine operations.

The numbers conclude that masonry clay brick, wood, cement, concrete and mineral insulations are the top five major constituents of the building envelope. The relevant environmental impacts of the aforementioned materials will be discussed in the results section (see 4.6).

Material	Quantity (M^3)	Distance to site (KM)	Wastage on site
Masonry clay brick	155,4	60	5%
wood	143,5	300	17%
cement	106,36	100	13%
ready mix concrete	52	60	4%
woodwool and mineral insulations	30,5	60	13%
glass	17	380	N/A
gypsum	5,2	85	12.5%
ceramics and porcelain	5	320	10%
steel	4,2	370	3.3%
aluminium	1,4	470	7.5%
plastics	0,8	350	N/A

Table 4 Predominant materials in the building under study with relevant quantities, transport distances and wastage on site. Source of data: NL Project Team and One Click LCA, 2015.

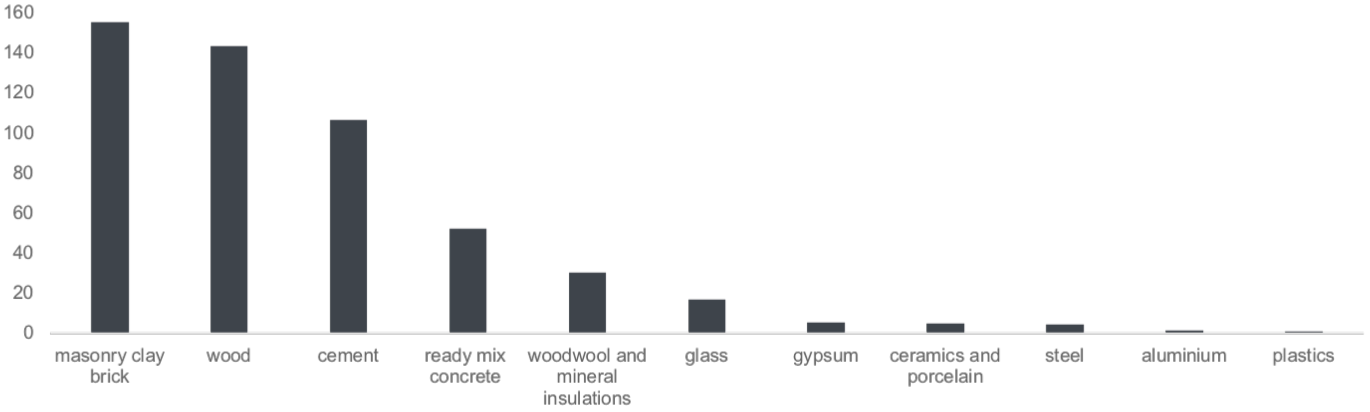


Figure 23 Main materials and their share in the building envelope. Source of data: NL Project Team and One Click LCA, 2015.

4.6 LIFE CYCLE ASSESSMENT OVERVIEW

Based on the input information and the building inventory, the LCA model has was generated in the One Click LCA. The software is set according to the European Standard EN 15978 and covers the life cycle stages from cradle to grave, with separate reporting to product stage, construction process, use stage, operational energy, and end of life. One Click LCA software and its embedded datasets are compliant with ISO 14040/14044 or EN 15804, and with the Active House Specification requirements as well (One Click LCA, 2015).

The environmental indicators situated in the LCA analysis are as following:

1. **GWP (global Warming Potential)** as an indicator demonstrating the greenhouse effect; When the quantity of greenhouse gasses in the atmosphere increases, the atmospheric layers near the earth are heated up, resulting in climate change.

2. **AP (Acidification Potential)** as an indicator demonstrating the acid rain phenomenon; When acidifying substances react with water and falls as 'acid rain', this leads to, among other things, decomposition of root systems and leaching of nutrients from plants.

3. **EP (Eutrophication Potential)** as an indicator demonstrating the surface water Eutrophication; An excessive supply of nutrients generates unwanted plant growth in delicate ecosystems, for example the growth of algae which results in the fish death.

4. **ODP (Ozone Depletion Potential)** as an indicator demonstrating the stratospheric ozone depletion phenomenon; Depletion of the stratospheric ozone layer which protects flora and fauna against the sun`s harmful UV-A and UV-B radiation.

5. **POCP (Photochemical Ozone Creation Potential)** as an indicator demonstrating the Formation of ozone of lower atmosphere or photo-smog; Contributes in connection with UV radiation to the formation of ozone in the lower atmosphere (summer smog) which is damaging to the respiratory system, etc.

6. **GER (Gross Energy Requirement)** as an indicator demonstrating the total use of primary energy excluding raw materials; Sum of Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials, and Use of renewable primary energy excluding renewable primary energy resources used as raw materials.

And lastly:

7. **Biogenic carbon storage**; Biogenic carbon sequestered in materials (in case of A1-A3) or in growing vegetation (in case of B1), expressed as CO^2-equivalent. This biogenic carbon may or may not be preserved after the asset lifetime depending on the end of life process for said

materials. This impact category is separate from accounting of the fossil GWP.
(Blengini, 2007 and One Click LCA, 2015)

The aforementioned, make the bases of characterization in the life cycle impact assessment.

As of the pre-use stage, the materials have been chosen mostly from local suppliers, or the nearest ones, in the cases of absent local supplier. Transportation distances have been calculated and deployed automatically by the software to chosen materials.

As of end-of-life, a recycling scenario has been adopted for the building materials and elements; lithoid materials are generally assumed to be crushed, for uses such as recycled concrete aggregate, subbase filing, and backfilling rock. Wooden elements are to be incinerated for energy recover, and other products including steel and other metals, glass, gypsum and plastic would be individually recycled. Landfilling option has been eliminated from the end-of-life scenarios in this research. An overview of the EOL scenarios dedicated for the materials and components of the building is shown in table 5.

Carbon emissions and benchmark:

Embodied carbon of buildings contributes to around 11% of the entire global carbon emissions (World GBC, 2019 and One Click LCA, 2015) and thus, any step towards reducing it is vital for the climate emergency. Reducing embodied carbon, as introduced by One Click LCA, starts with two key steps:

- Set up reduction targets based on the building type and local construction practices
- Compare material life cycle impacts and choose the low-carbon solutions

(One Click LCA, 2015)

The One Click LCA software provides a feature that calculates the embodied carbon based on the data compiled from thousands of anonymized, verified building projects using One Click LCA software. The benchmark adopted in this analysis, as recommended by the software, is a Performance metric Carbon Benchmark (A1-A4, B4-B5, C1-C4) for Western Europe as of 2020. The retained sample size includes 431 projects. Data is collected predominantly from the United Kingdom (134 projects), France (91 projects) and Spain (72 projects). Data is included into the benchmarks based on mechanical and manual screening that considers consistency, completeness and plausibility. Projects that display aberrant values or inconsistency have been excluded from sample, according to One Click LCA, 2015. The carbon benchmark for the building under study is displayed in figure 24. It indicates a relatively high level of embodied carbon for this building. The performance metrics A to G include the range of results at two standard deviations of the mean for the building type. The range is divided into seven bands equally distributed. The mean of the results falls within band “D”, and the lower and upper extremes of the range are in bands “A” and “G”, respectively (One Click LCA, 2015).

The A phase of the building life cycle, or the materials and construction stage, accounts for the highest levels of embodied carbon. Building’s load bearing and distribution system, including horizontal and vertical structural elements have the largest levels of embodied carbon among the other elements.

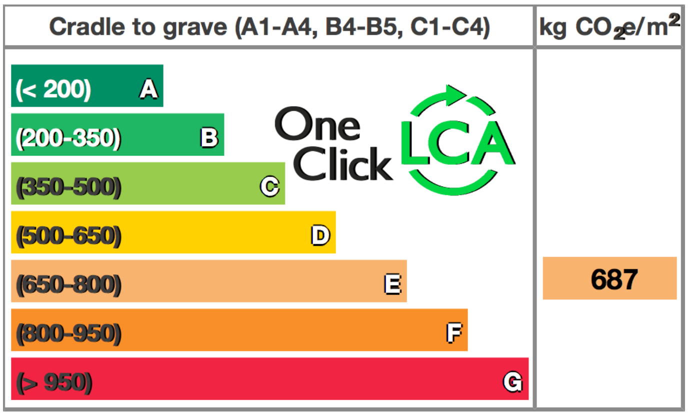


Figure 24 Embodied carbon and carbon benchmark of the building, One Click LCA, 2015.

Material/Component	EOL Scenario	Wastage on site
concrete cladding	crushing to aggregate	4%
concrete elements (foundations)	crushing to aggregate	4%
steel elements (others)	recycling	3.3%
steel elements (structure)	recycling	3.3%
steel elements (concrete rebar)	recycling	4.85%
bitumen layers	recycling/landfill	10%
masonary clay bricks	crushing to subbase aggregate	5%
mortar, cement mortar, tile adhesives	curshing for backfill use/landfill	13%
plywood	wood incineration	16.7%
massive wood	wood incineration	17.9%
wood elements (structure+others)	wood incineration	17.9%
particle board	wood incineration	17.9%
plasterboards	recycling	16.7%
stucco	recycling	12.5%
ceramics	crushing to subbase aggregate	10%
aluminium elements	recycling	10%
wood wool panels	wood incineration/landfill	7.5%
mineral fiber boards	recycling/landfill	8%
linoleoum carpets	recycling	8%
natural stone	crushing to aggregate	10%
sanitary objects (porcelaind & steel)	reuse	4.5%
wooden doors and windows	reuse	0%
metal doors and windows	reuse	0%
technical installations	reuse	0%

Table 5 End-of-Life scenario adopted for the materials and components existing in the building with default wastage on site. Source of data: Author and One Click LCA, 2015.

4.7 IMPACT ASSESSMENT AND INTERPRETATION OF RESULTS

The life cycle impact assessment (LCIA) has been conducted with the characterization method for the building under study. The achieved results according the adopted indicators and in compliance with EN 15978 are summarized in table 6.

The characterization is based on a cradle to gate approach. Hence, the impacts demonstrated in phase D are beyond the scope of a conventional building life cycle; these figures represent the net environmental gains which would be obtained when reuse or recycling end-of-life scenarios are planned to be applied to the building at the end of its life cycle (after demolition).

Section	Result category	Global warming kg CO_2e	Acidification kg SO_2e	Eutrophication kg PO_4e	Ozone depletion potential kg CFC_{11}e	Formation of ozone of lower atmosphere kg Ethenee	Total use of primary energy ex. raw materials MJ	Biogenic carbon storage kg CO^2e bio
A1-A3	**Construction Materials**	**6,74E+05**	**2,34E+03**	**4,29E+02**	**4,80E-02**	**2,07E+02**	**8,51E+06**	**1,71E+05**
A4	**Transportation to site**	**6,21E+03**	**2,45E+01**	**5,30E+00**	**1,20E-03**	**4,90E-01**	**1,63E+05**	
A5	**Construction/installation process**	**2,24E+05**	**4,12E+02**	**1,40E+02**	**3,70E-02**	**3,27E+01**	**3,56E+06**	
B1-B5	**Maintenance and material replacement**	**1,63E+05**	**9,74E+02**	**1,64E+02**	**3,30E-02**	**7,12E+01**	**3,66E+06**	
B6	**Energy use**	**5,45E+05**	**1,71E+03**	**1,44E+02**	**4,50E-02**	**1,10E+02**	**8,88E+06**	
B7	**Water use**	**1,04E+04**	**7,27E+01**	**2,08E+02**	**1,00E-03**	**3,05E+00**	**1,87E+05**	
C1-C4 ▼	**End of life**	**1,12E+04**	**4,54E+01**	**1,05E+01**	**1,90E-03**	**1,44E+00**	**2,47E+05**	
C1	Deconstruction/demolition	4,32E+03	8,00E+00	1,52E+00	7,00E-04	6,60E-01	7,65E+04	0,00E+00
C2	Waste transportation	5,11E+03	2,34E+01	5,09E+00	1,00E-03	3,00E-01	1,46E+05	
C3	Waste processing	1,75E+03	1,38E+01	3,88E+00	2,00E-04	4,70E-01	2,42E+04	
C4	Waste disposal	2,28E+01	1,70E-01	3,60E-02	4,10E-06	4,60E-03	3,34E+02	
D ▼	**External impacts (not included in totals)**	**-3,73E+05**	**-1,18E+03**	**-1,93E+02**	**-4,10E-02**	**-1,20E+02**	**-5,79E+06**	**-1,23E+04**
A5-benefit	Construction site - material wastage - benefit	-1,84E+04	-5,06E+01	-6,62E+00	-2,30E-03	-3,94E+00	-2,77E+05	-9,11E+02
D	Installed Materials - benefit	-3,55E+05	-1,13E+03	-1,87E+02	-3,89E-02	-1,16E+02	-5,52E+06	-1,14E+04
	Total	**1,63E+06**	**5,58E+03**	**1,10E+03**	**1,67E-01**	**4,25E+02**	**2,52E+07**	**1,71E+05**

Table 6 Summary of life cycle assessment results according to EN-15978, One Click LCA, 2015.

The results demonstrate that the pre-use stage, including the phases A1 to A5, dominates the environmental impacts caused by the building. It is perceived from the results that, based on the assumed materials selected in the inventory analysis, the A1 to A5 modules contribute to the highest levels of ODP and Bio-CO_2 storage.

It is not surprising that the use phase of the building with a conventional type, although out of the scope of this research and hence only roughly looked at, has the second place among the life stages that has highest levels of environmental impacts, GER and GWP in particular, of the building during its entire life cycle.

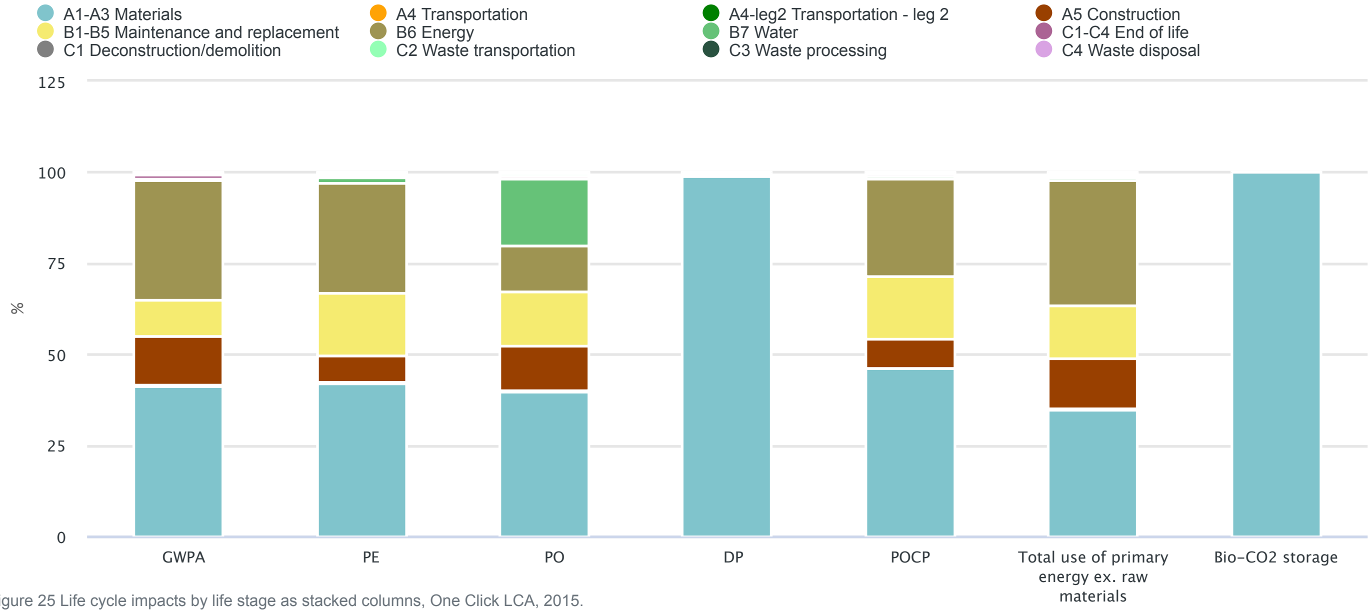


Figure 25 Life cycle impacts by life stage as stacked columns, One Click LCA, 2015.

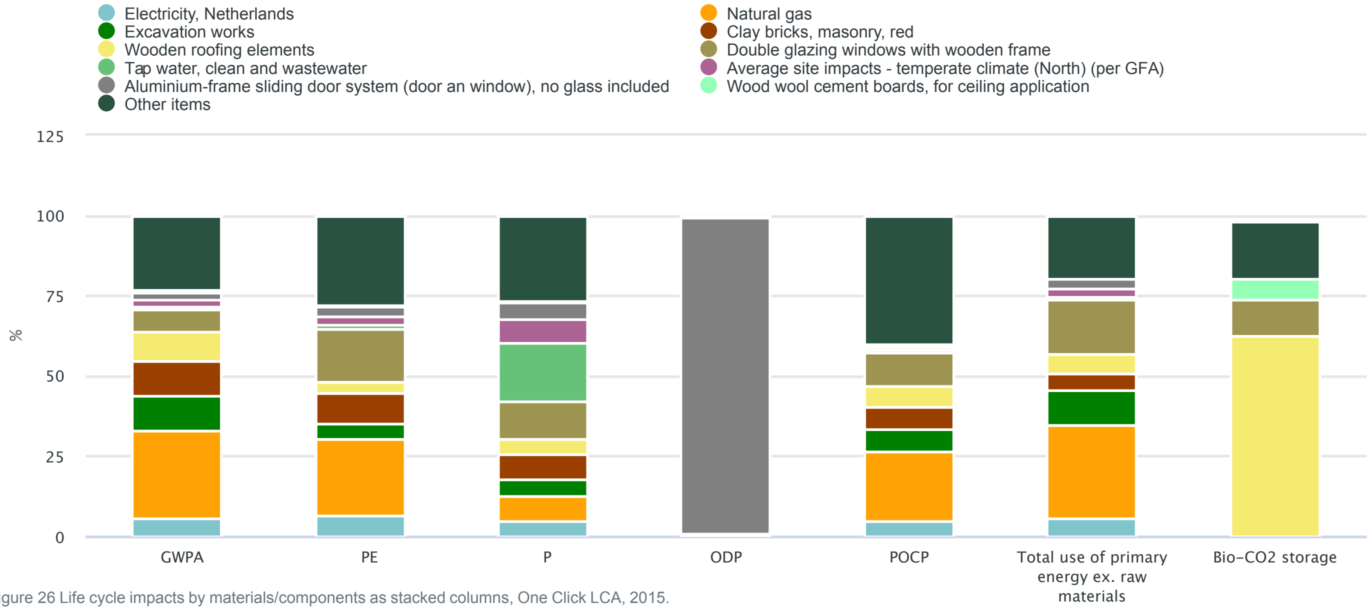


Figure 26 Life cycle impacts by materials/components as stacked columns, One Click LCA, 2015.

Having the impact share of the use phase of the building in mind, the stages of B1 to B7 were excluded from the results. Accordingly, the graphs in the following demonstrate the impacts only during pre-use and end-of-life stages of the building's life cycle. The use-phase has been left out of the results.

The results of the impact assessment for the use phase would provide the basis for future studies which would focus on impact reduction and efficiency improvement during the buildings operational phase; this is, hence, beyond the scope and objectives of this research.

For better understanding of the reader, a description of each life cycle phase, from A to D, according to One Click LCA, are presented in the following:

- **A1-A3:** Construction materials; product stage, cradle to gate. This covers impacts of a prod-uct or material that is ready to ship to construction site, including raw materials extraction, transport and manufacturing emissions. In case recycled or reused materials are used in this stage, their emissions may be accounted as zero. For the building under study, only virgin materials have been assumed in the inventory analysis.

- **A4:** Transport to construction site. This covers impacts of a product transport from the factory to the construction site. The transport chain may include interim steps through whole-saler or storage. In cases where transport vehicle can be used for other transport for a re-turn trip, only the actual transport required by the products are considered. For this project, no second leg of transportation and no return way have been taken into account.

- **A5:** Construction and installation process; construction site energy and water use, waste management and other environmental impacts, including material wastage on site.

- **B1-B5:** Maintenance and material replacement; this includes environmental impacts from replacing building products after they reach the end of their service life. The emissions cov-er impacts from raw material supply, transportation and production of the replacing new material as well as the impacts from manufacturing the replacing material as well as han-dling of waste until the end of waste state. This module is beyond the scope of this re-search.

- **B6:** Energy use; operational energy. This covers all building energy import (including elec-tricity, district heat and cooling and fuels. Any energy produced from renewables on the site is not in the scope (excluding any fuels or imported electricity needed to produce it), during the operational phase. Exported energy is not deduced from this. This does not cover plug loads (tenant energy use), which is outside of the assessment. This module is beyond the scope of this research.

- **B7:** Water use; water use of the building systems and building envelope (excluding in the standard accounting, the water use of tenants), during the operational phase. This covers the life cycle environmental impacts of water, including production and transportation and waste water treatment. This module is beyond the scope of this research.

- **C1-C4:** End of life; this includes impacts for processing recyclable construction waste flows for recycling (C3) until the end of waste stage or the impacts of pre-processing and land-filling for waste streams that cannot be recycled (C4) based on type of material. Additionally deconstruction impacts includes emissions caused by waste energy recovery.

- **D:** External impacts; not included in the total; this module contains the benefits and loads beyond the asset life-cycle (system boundary). This information module provides transpar-ency for the environmental benefits or loads resulting from reusable products, recyclable materials and/or useful energy carriers leaving a product system e.g. as secondary materials or fuels or in form of exported energy.

(One Click LCA, 2015)

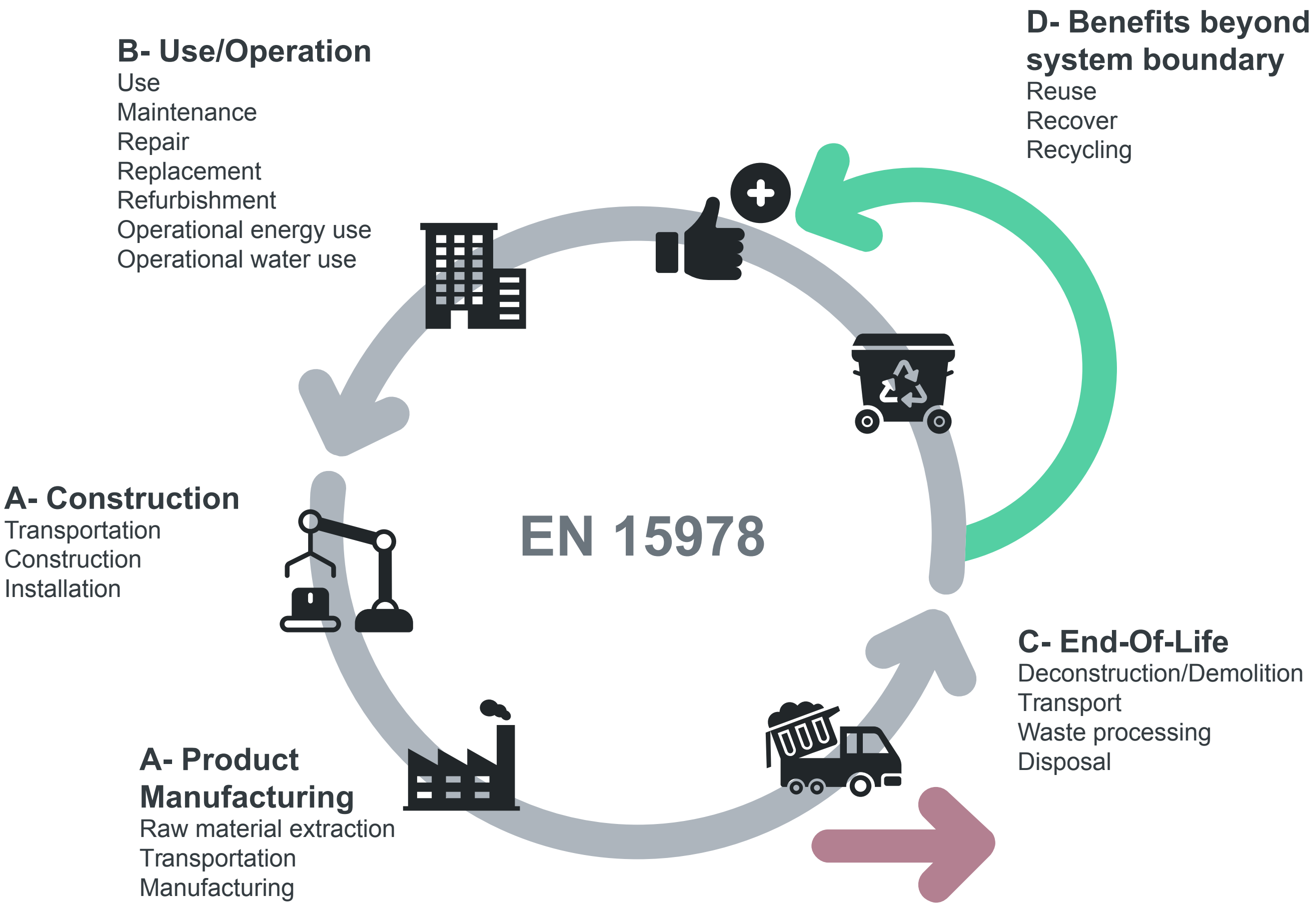


Figure 27 Life cycle stages of a building according to the EN15978; the figure includes the D phase at the end of the life cycle as benefits beyond the system boundary. This would replicate a Cradle to Cradle approach, provided the D module applied to the plannings. Data retrieved from www.greenbuildingfactory.com, graph regenerated by author, 2021, Icons from thenounproject.com.

In the following figures, the contribution of different life stages as well as the classification of each material to the individual impact categories is displayed. The purpose of this section is to provide a visual breakdown of results per environmental impact indicator. The construction site scenarios are defined as an assumed average production of construction waste 5 kg/m2 (GFA), general construction waste; assumed electricity use of 37 kWh/m2 (GFA); assumed total use of diesel 4.5 l/m2 (GFA). The scenario was selected according to the EN15804 for European temperate climate.

Global Warming Potential:
Floors, ceilings, roofs and load bearing beams are top elements in global warming potential, followed by the building openings that include wooden and aluminum frame doors and windows. Afterwards are the construction site scenarios as well as exterior walls and facades that are the second and the third large classes with high global warming potential.

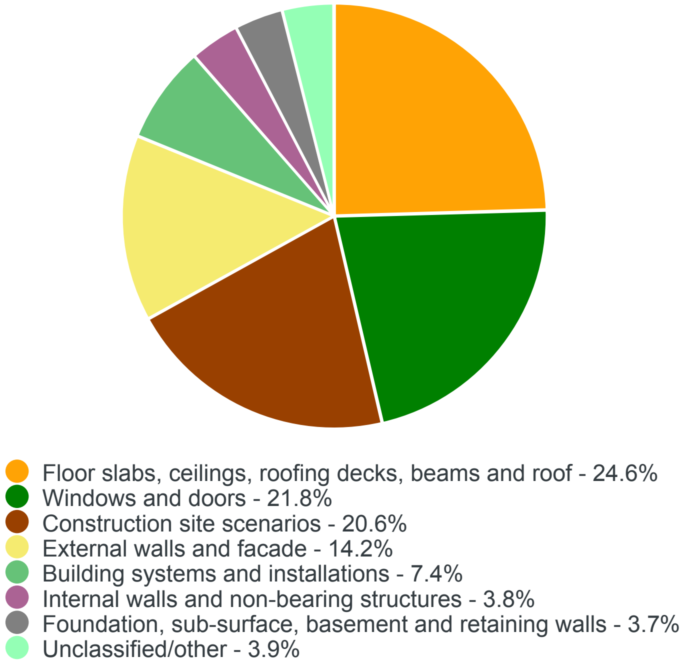


Figure 28 Global warming potential KG CO$_2$e per building component classification, One Click LCA, 2015.

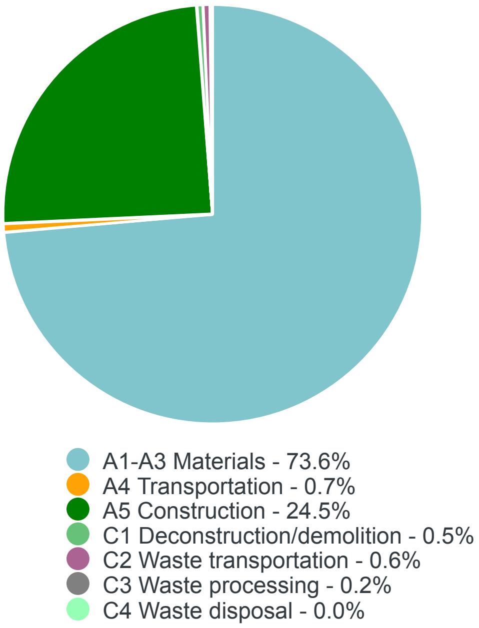


Figure 29 Global warming potential KG CO$_2$e per life cycle stage, One Click LCA, 2015.

A1-A3 and A5 stages come along with remarkable global warming potential. Transportation does not have a huge share, though. Stages in C module do not have a large potential either. Global warming potential KG CO$_2$e per life cycle stage, One Click LCA, 2015.

Acidification:
Windows and doors have noticeably high acidification potential, which is a bit below half of the to-tal. Floors, ceilings, roofs and beams have

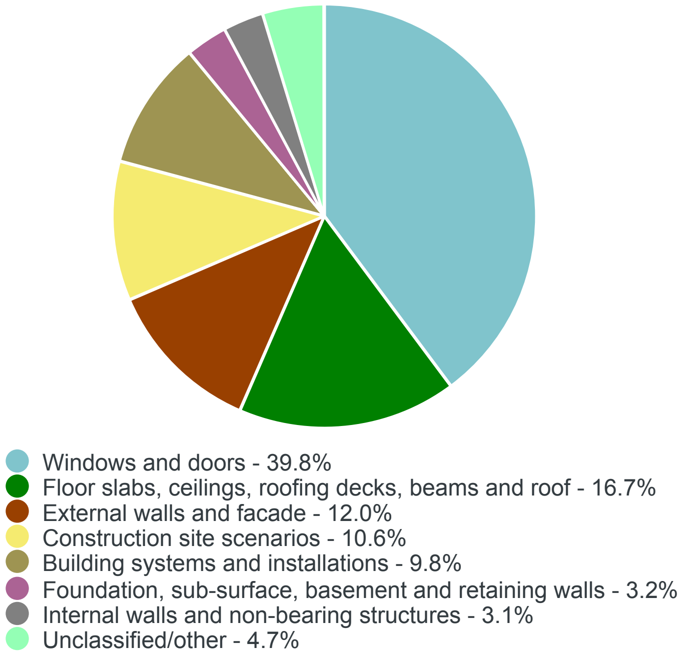


Figure 30 Acidification potential KG SO$_2$e per building component classification, One Click LCA, 2015.

the second place. Construction site scenarios and external walls are followed and come without a major difference in percentage.

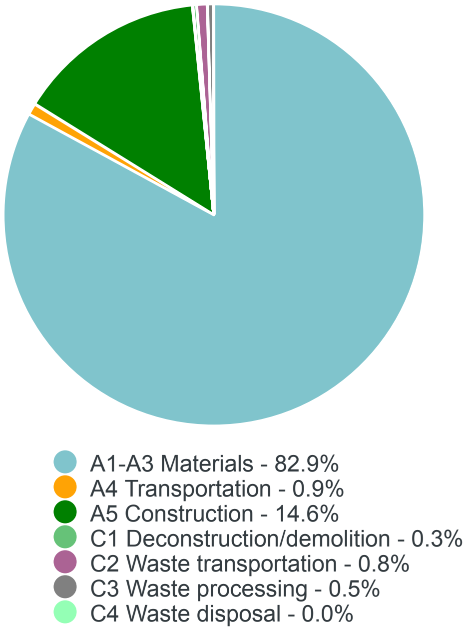


Figure 31 Acidification potential KG SO$_2$e per life cycle stage, One Click LCA, 2015.

A1-A3 phases dominate the other phase with 82.1% acidification potential among the total. C1-C4 stages own the third rank in acidification potential. Transportation has a very small share.

Eutrophication:

Eutrophication occurs majorly through the manufacturing of windows and doors. Construction site scenarios have the second large share in eutrophication impacts. Floors, ceilings, roofs and beams account for 17.3% of potential and seems to be relatively high.

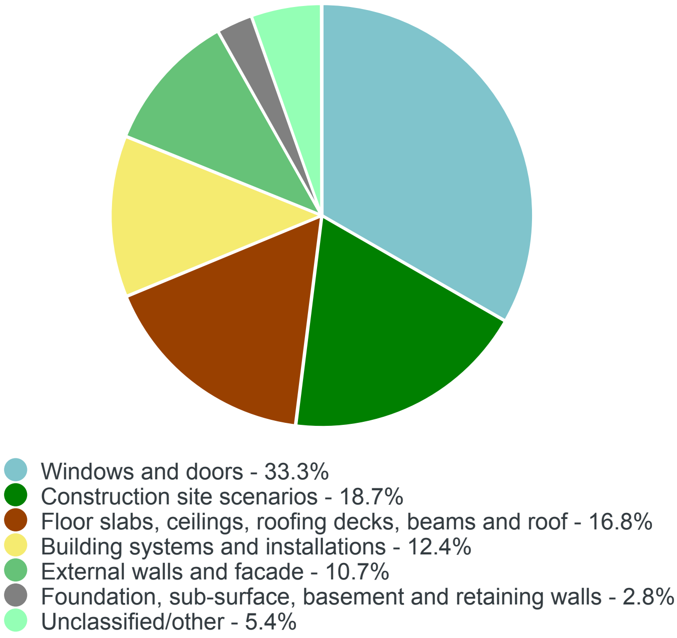


Figure 32 Eutrophication potential KG PO$_4$e per building component classification, One Click LCA, 2015.

A1-A3 phases have the largest share of eutrophication potential. Construction stage A5 accounts for around 23% of the total. Transportation has a very small share.

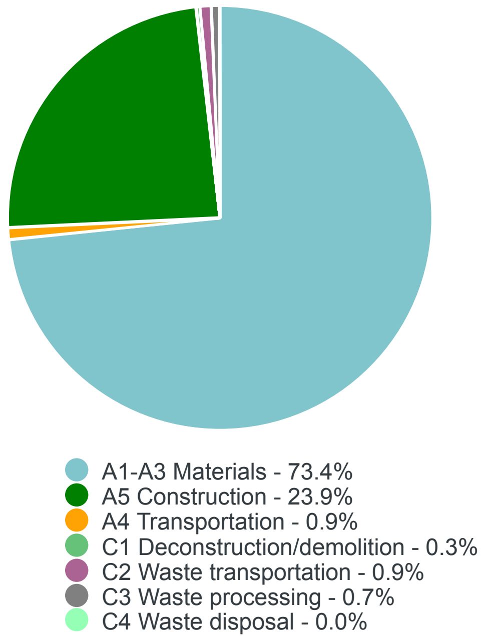


Figure 33 Eutrophication potential KG PO_4e per life cycle stage, One Click LCA, 2015.

Ozone Depletion Potential:

As of ozone depletion, the building systems and installations as well as the construction scenarios are the two categories with the highest potential.

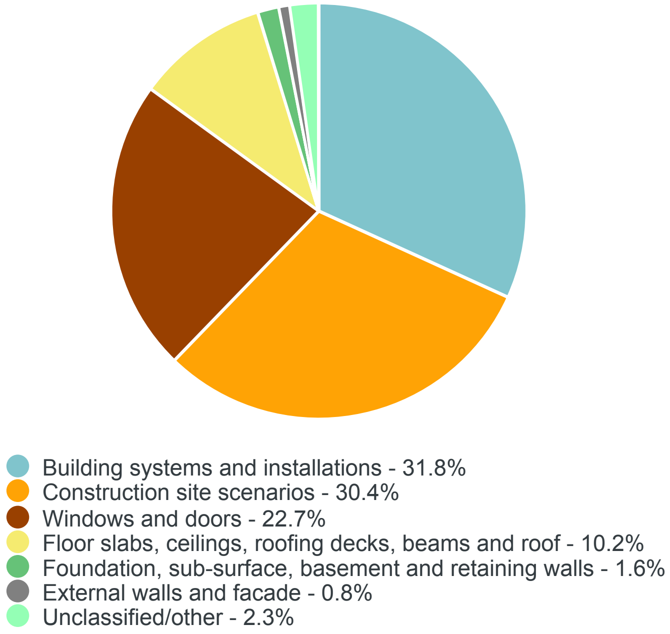


Figure 34 Ozone depletion potential KG CFC11e per building component classification, One Click LCA, 2015.

Water heating equipment have the biggest share among the installation systems. Windows and doors are the next category and are followed by floors, ceilings, roofs and beams. Windows and doors are the next category and are followed by floors, ceilings, roofs and beams.

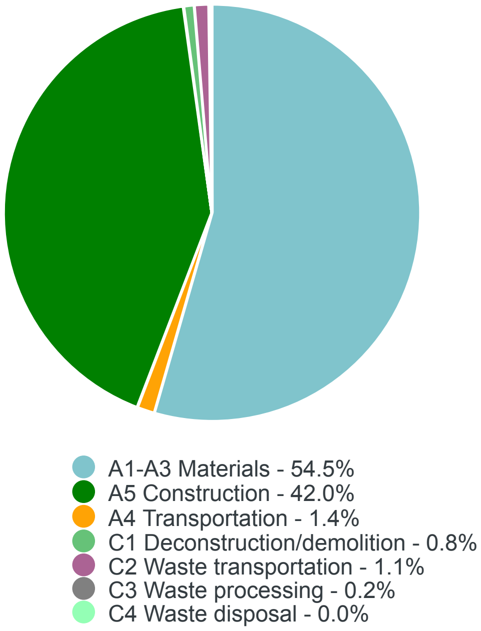


Figure 35 Ozone depletion potential KG CFC11e per life cycle stage, One Click LCA, 2015.

Ozone depletion potential exists predominantly in the A1-A3 and A5 stages of the building's life cycle. The share of the two together reaches beyond 90% of the total ODP of the building.

Photochemical ozone formation

Floors, ceilings, roofs and beams, as well as windows and doors are the top large contributors to the photochemical ozone formation. The two categories together have a share of more than half of the total. Internal walls and non-load bearing elements have the smallest share.

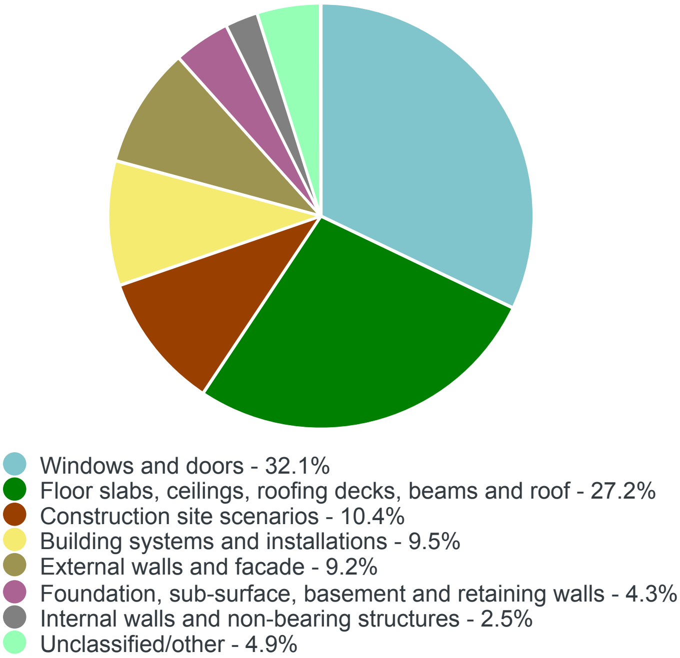


Figure 36 Formation of Ozone of lower atmosphere KG Ethenee per building component classification, One Click LCA, 2015.

A1-A5 stages have the largest share of contribution to the formation of photochemical ozone in the lower levels of atmosphere.

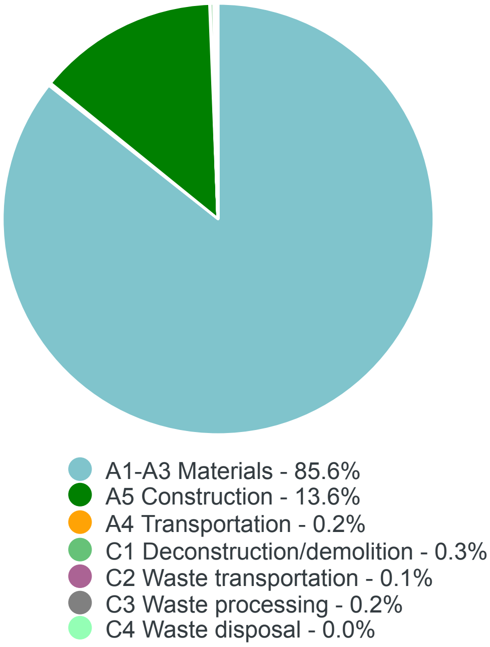


Figure 37 Formation of Ozone of lower atmosphere KG Ethenee per life cycle stage,One Click LCA, 2015.

A1-A3 own the first place with nearly 86% contribution.

Total energy consumption:

The cradle to gate process for windows and doors comes along with around 35% of building’s entire primary energy consumption. Construction site scenarios as well as floors, ceilings, roofs and beams are at the second and the third place, respectively, with regards to the total primary energy use of the building.

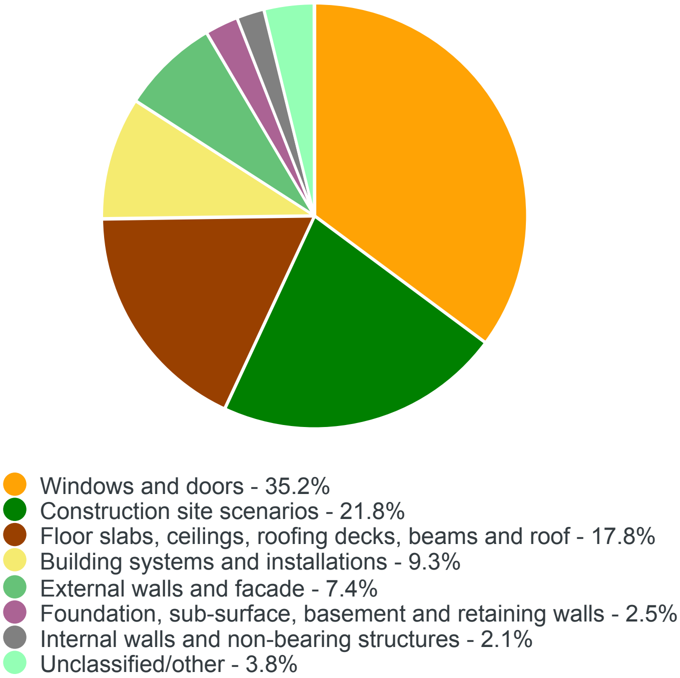


Figure 38 Total use of primary energy ex. raw materials MJ per building component classification,One Click LCA, 2015.

It is important to mention here again, as already stated in the beginning of this chapter, that the positions relevant to the use-phase of the building, including water, energy and fuel use, as well as the building maintenance phase, have been excluded from the results, since they stand beyond the scope of this research. Hence, the total primary energy consumption would refer only to the pre-use and end-of-life stages of the building's life cycle.

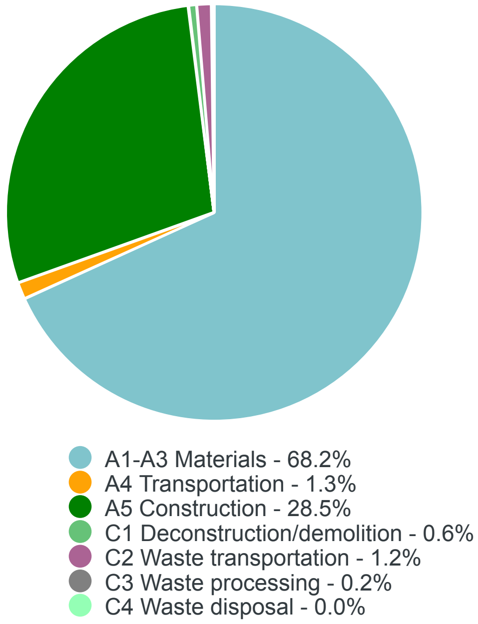


Figure 39 Total use of primary energy ex. raw materials MJ per life cycle stage,One Click LCA, 2015.

As shown in the graphs, the A1-A3 use the most primary energy. Then there is the construction phase, A5, that consumes a bit less than 28% of the entire primary energy.

Biogenic carbon storage:

Floors, ceilings, roofs and beams have the largest amounts of biogenic carbon stored in them. The share of this category reaches 75,5% of the total.

The main reason for this, would be the share of wooden elements that exist in this category.

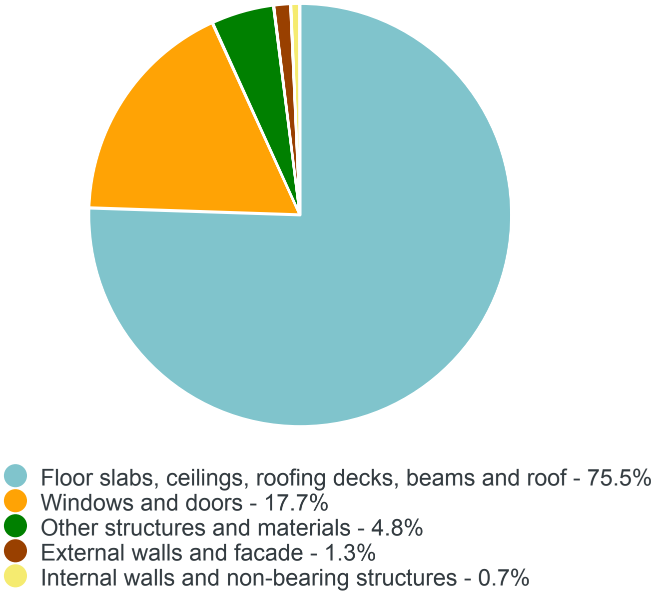


Figure 40 Biogenic carbon storage KG CO_2e bio per building component classification, One Click LCA, 2015.

The share of wood in storing biogenic carbon is around 70% of the total, from which 90% goes to timber wood elements.

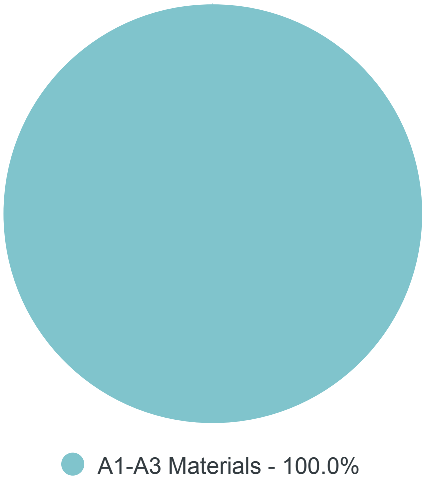


Figure 41 Biogenic carbon storage KG CO_2e bio per life cycle stage, One Click LCA, 2015.

As of life cycle stages, no stage contributes to the biogenic carbon storage, except A1-A3 stages, described as cradle to gate.

4.8 SYNTHESIS

In the next step, in order to conclude the analysis results, the predominant materials constituting the building were classified based on their size of contribution to the environmental impacts. The LCI results revealed that the categories of floors, ceilings, roofs and beams, doors and windows, external walls and facades, as well as foundation and load bearing system have the highest share of contribution, although with different ratios, to almost all of the environmental impact indicators. Based on the data retrieved from the inventory analysis, the building's major materials which are also mostly present in the mentioned categories, are as displayed in figure 42, along with the environmental impact indicators for each individual material as stacked columns. Doors and windows are considered as an individual category, due to the mixed type of the materials that constitute them.

The result synthesis was done in order to identify the material categories in hotspot with required recovery action. Recovering as downcycling or recycling of certain construction materials would result in cutting down the building construction and demolition waste that delivers various benefits , including reduction of need for disposal facilities as well as potentially reducing the associated environmental issues, reduction of space required for landfilling, and offsetting the environmental impacts associated with the extraction and use of virgin resources and production of new materials (US EPA, 2016). This would include all the supplying stages from mining, processing, manufacturing and transportation to site. In the section 5 of this research, the most eligible demolition/ deconstruction methodology proposed for the dominant materials, as concluded in this section, will be discussed.

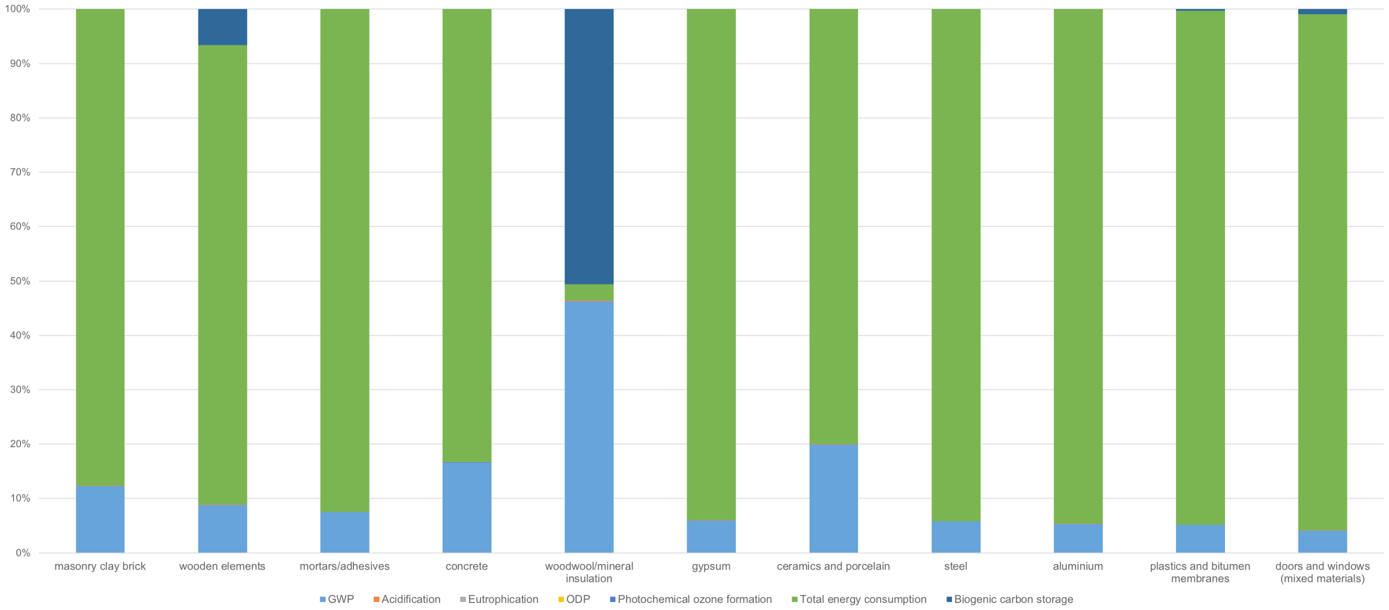


Figure 42 Contribution of building materials to the environmental impacts of the pre-use phase, One Click LCA, 2015.

As explained in the beginning of this section, the parameters set to the LCA performed in this research, include a proper end-of-life scenario for the materials and components that constitute the building envelope. The adopted scenarios include recycling or reuse of the materials; landfilling has been omitted as an EOL scenario. Though, the numbers relevant to the D stage are not included in the total result numbers. Nevertheless, in a parallel attempt, a secondary model of the building was generated in the software, in which no recycling or reuse scenario have been obtained for any of the materials. Instead, landfilling was adopted as the only scenario for EOL processing. As a result, the numbers for stages A1 to B7 remained unchanged, but the numbers of the C and the D stage varied between the two models; the difference that occurred in the results are displayed in figure 43, as well as tables 7 and 8. The comparison between the two models revealed that with a recycling EOL scenario, there will be higher C phase emissions, but there are also much more benefits to come back to the cycle, as D phase.

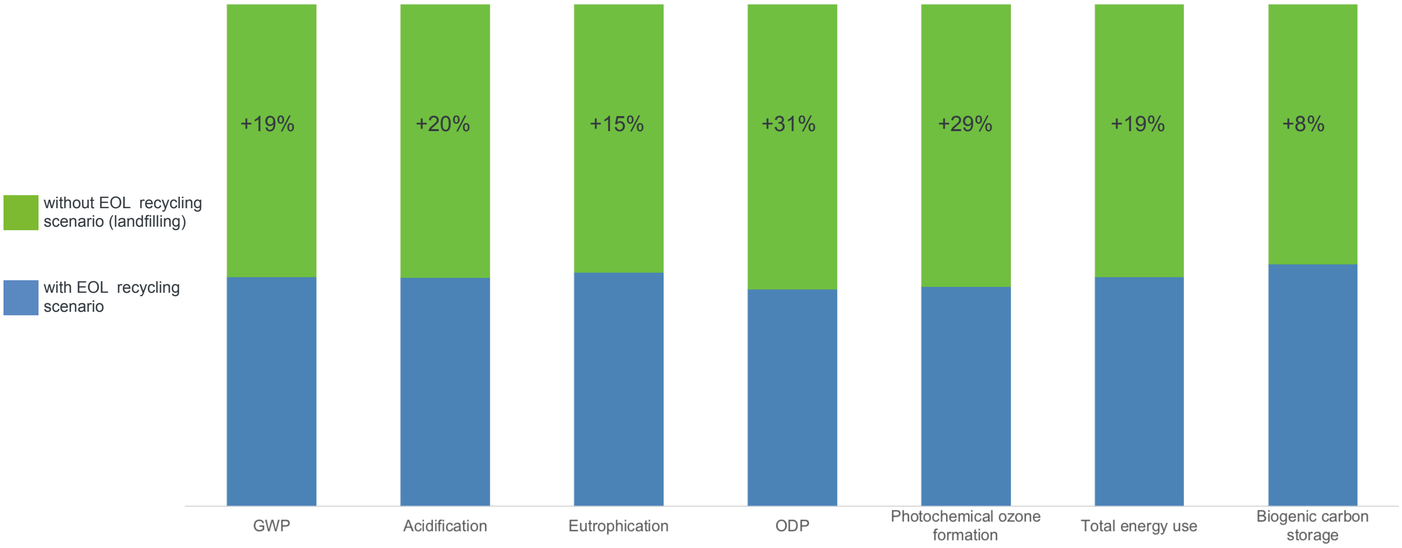


Figure 43 Comparison of LCA results for each impact indicator for the two models: one with recycling scenarios applied to the EOL, one with only landfilling. Increase in environmental impacts per indicator is visible. One Click LCA, 2015.

Life Cycle Stage	GWP	Acidification	Eutrophication	ODP	Photochemical ozone formation	Total energy use	Biogenic carbon storage
C1-C4	1,12E+04	4,54E+01	1,05E+01	1,90E-03	1,44E+00	2,47E+05	0
D	-3,73E+05	-1,18E+03	-1,93E+02	-4,10E-02	-1,20E+02	-5,79E+06	-1,23E+04
Total (all stages A-D)	1,26E+06	4,40E+03	9,08E+02	1,26E-01	3,05E+02	1,94E+07	1,59E+05

Table 7 LCA results characterization per impact indicator for life cycle stages C1-C4 and D, with recycling/reuse EOL scenario applied. One Click LCA, 2015.

Life Cycle Stage	GWP	Acidification	Eutrophication	ODP	Photochemical ozone formation	Total energy use	Biogenic carbon storage
C1-C4	8,94E+03	3,54E+01	7,43E+00	1,60E-03	1,27E+00	1,78E+05	0
D	-1,26E+05	-2,87E+02	-5,64E+01	-1,30E-03	-3,23E+01	-1,95E+06	-1,23E+04
Total (all stages A-D)	1,51E+06	5,28E+03	1,04E+03	1,66E-01	3,93E+02	2,32E+07	1,71E+05

Table 8 LCA results characterization per impact indicator for life cycle stages C1-C4 and D, with no recycling/reuse EOL scenario applied => only landfilling. One Click LCA, 2015.

4.8 BUILDING CIRCULARITY

In addition to the life cycle impact assessment, a building circularity was performed using the provided feature in the One Click LCA software. The Building Circularity tool allows tracking, quantifying and optimizing the circularity of materials sourced and used during the building life-cycle, as well as the circularity at the end of life. It allows getting a holistic picture, as well as a detailed breakdown per material type. The goal of the Building Circularity tool is to calculate the circularity percentage of the building.

When the project supports, the building circularity tool also supports applying Design for Disassembly and Design for Adaptability principles. This tool can be used for HQE Economie Circulaire, London Plan Circularity Statement, Ellen McArthur Foundation Circularity Indicators as well as other circular design purposes (One Click LCA, 2015).

The building circularity feature provided by One Click LCA, consists of the material query step, circularity weighting score, and calculation period. The material query works aligned with the materials inventory information. The circularity weighting score differs for each individual material; the recommended weighting scores by the software have been adopted in this research. The calculation time matches the building's service life.

As a pre-assumption for the building under the study in this research, no recycled, reused or renewable materials have been entered in the material inventory. Therefore, the building circularity results does not come out with high percentages, since only virgin materials were inventoried. Moreover, due to the conventional, old type of the building envelope, there were no materials or components with Design for Disassembly or Design for Adaptability principles inventoried. Though, for any new building that would be erected in the future phases of the project (see section 1.3, project introduction) such principles are recommended to be taken into account during the design phase.

The values relevant to the material wastage on site the end-of-life scenarios calculated in the circularity analysis, are adopted from the inputs to the LCA database. Followed by what was explained in the LCA results section, recycling and/or reuse scenarios were selected for all of the materials and components that the building consists of.

In fact, the building circularity score represents the total materials circularity both in use of the materials in the building as well as end of life processes. It is calculated as the average of materials recovered, representing use of circular materials in the project (which is nearly zero in this study) and the materials returned, representing how effectively materials are returned, instead of disposed of or downgraded in value, based on the dedicated EOL scenario. The circulation is totally mass based without material weighting.

The result of the building circularity is shown in the following figures; here again, similar to the LCA analysis, a second model of the building is generated, in which no recycling/reuse scenario is adopted for the end-of-life. In this secondary model, only landfilling is adopted for handling the building materials and components at the end of their life. The comparison of the two models reveals a remarkable difference in the circularity score.

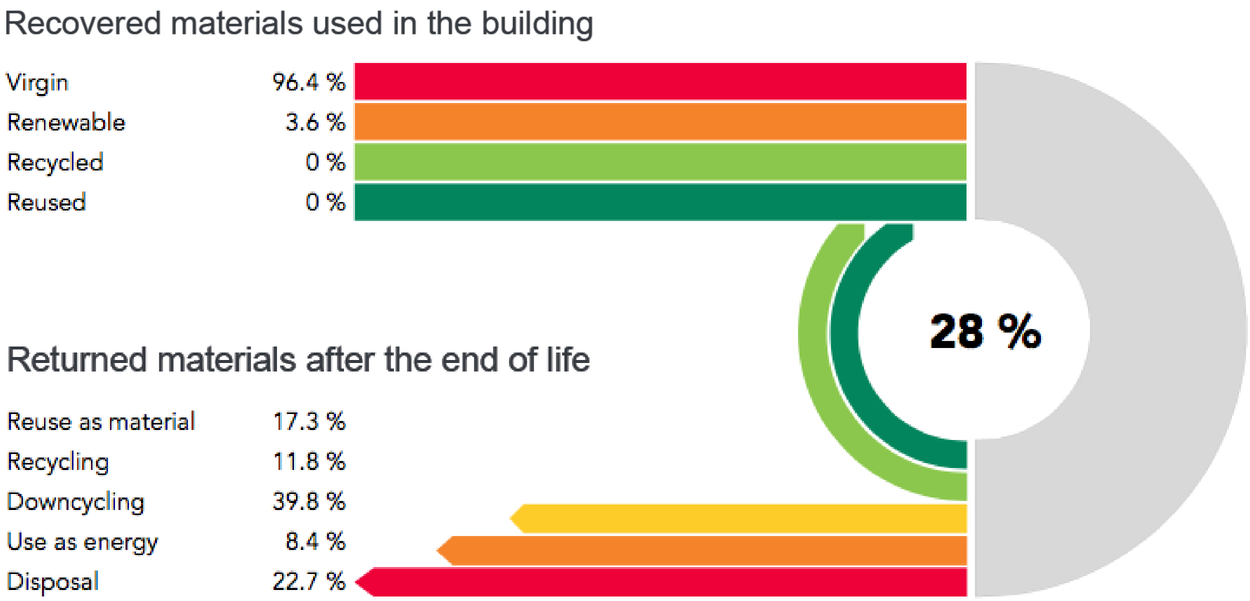


Figure 44 Building circularity score with recycling scenarios applied to the EOL. One Click LCA, 2015.

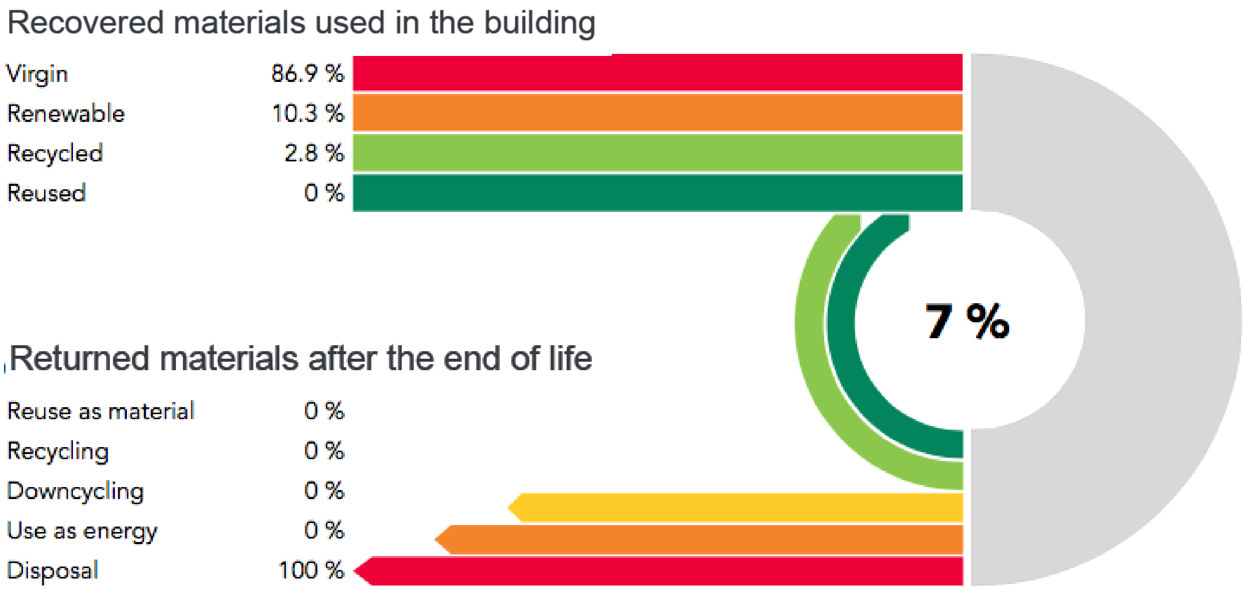


Figure 45 Building circularity score with no recycling/reuse EOL scenario applied => only landfilling. One Click LCA, 2015.

“Circular Economy – An economic system where products and services move in closed loops or circles by employing reuse, sharing, refurbishment, recycling, and remanufacturing, with the goal of keeping products in use longer and thus increasing the productivity of a resource.”

PlaceEconomics

5. PROPOSAL

5.1 INTRODUCTION

Any constructed building is predicted to come to end of its operational life and be treated with any of the various currently existing end-of-life concepts. However, which measure will be taken once a building reaches its end of life, is a topic that the decision makers and project owners should conclude and determine. Figure 46, summarizes the possible end-of-life procedures that are frequently used for the current building stock (Bertino et al., 2021). The focus of this section in this research thesis, is the deconstruction method that is an ideal substitute for the conventional demolition.

Parallel to the boom in construction activities in cities, the masses of demolition waste is also increasing (Aidonis, D. et. al, 2008). Construction and Demolition Waste (CDW) constitutes the largest waste stream in the European Union, accounting for the generation of above 350 million tonnes/year construction waste, excluding excavated soil and dredging spoil. This waste stream is made from heterogeneous mixes of concrete, mortars, bricks, tiles, mineral aggregate, bitumen, metals, plastic, wood and organic lightweight particles (European Commission, 2017 and 2018).

Nevertheless, despite the noticeable growth of the global construction industry, the transition from a conservative economy to a circular one is still underdeveloped. Hence, new, improved methods as well as innovative services need to be generated and adopted by the businesses and decision makers in order to make reduction in the use of resources and raw materials, while cutting down the construction waste disposal amounts (Bertino et al., 2021).

Maintenance	Refurbishment	Demolition	Deconstruction
Process of interventions concerning repair, renovation, and replacement of building parts without altering the overall volume and without changing the intended use	Process of restoring a structure to a former better condition or to revive it, including alterations such as remodeling and retrofitting, which can result in a completely different building	Process of arbitrary disassembling or destroying of a building in order to quickly clear the construction site, with the use of heavy construction machineries	Process of selective dismantling of building components, part by part and avoiding damage, specifically for reuse, repurposing, and recycling
Quick and easy Constant over time Relatively cheap	Heritage preservation Relatively expensive	Quick and easy Very cheap Common method	Relatively labor-intensive Component reuse Material recycling

Figure 46 The mostly practiced building end-of-life concepts; definitions and characteristics. Bertino et al., 2021.

The EU Waste Framework Directive 2008/98/EC called all member states to take any necessary measure towards achieving a minimum of 70% re-use, recycling or other recovery of non-hazardous Construction and Demolition Waste by 2020 (Whittaker et al., 2021).

The principal objective of any demolition waste management strategy is to maximize raw material recovery from the construction rubble, as Aidonis D. et al., 2008 explain. The highest priority goes to the direct reuse of materials without them to lose the economic value through recycling (Aidonis, D. et. al, 2008).

Bertino et al., 2021 state that in the preferred hierarchical scale of material circularity, reuse stands above recycling; downcycling and disposal stand at the next lower levels respectively (Bertino et al., 2021).

Various literature have offered definitions for building’s end of life procedures, the conservative demolition and the novel deconstruction, with almost resembling details.

The first decent method is to demolish the entire building using manpower and special machinery, that has substituted a great part of the man work during the recent decades. The rubble would be then collected in containers and transported for further steps, either to recycling plants or to landfills, without any in advance on-site processing. However, in some seldom cases,

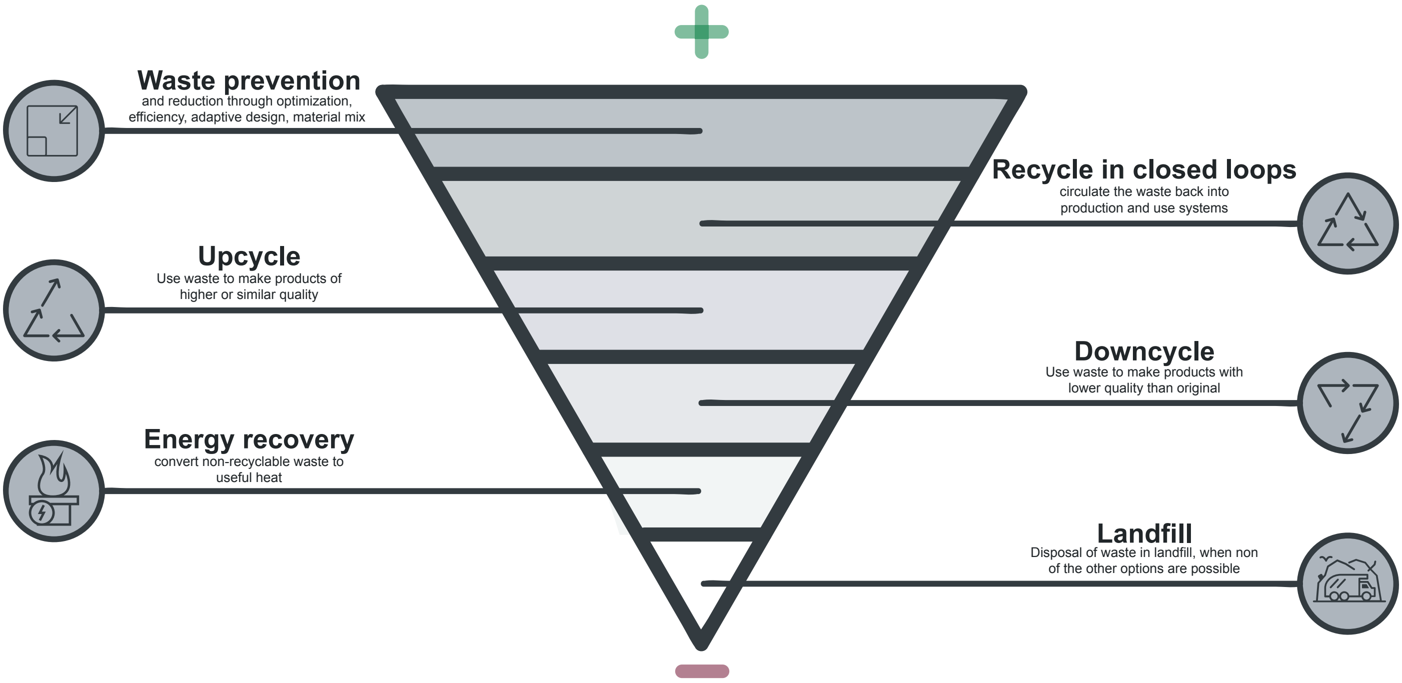


Figure 47 Hierarchy of waste from a circular economy point of view. Lacy et al., 2020. Data retrieved from: https://link.springer.com/chapter/10.1057/978-1-349-95968-6_2, graph regenerated by author, 2021, Icons from thenounproject.com.

a preliminary, but basic sorting and separation of materials takes place on site, right after the demolition (Aidonis, D. et. al, 2008).

The second method comprises of selective disassembly or “deconstruction” of the building components. The goal is to preserve the individual materials after separation, to be made available for reuse and recycling. In other words, the disassembly is performed in a way that maximizes the recovery potential of building materials, through separating and sorting. Particular building elements would be dismantled in this method, prior to the demolition of the entire building shell. As a result of using such disassembly and demolition method, more materials could be recovered, in comparison to the first conventional model, at a lower price and a quicker timeframe, hence, the materials life cycle would be extended. The demolition and separation procedure is then followed by processing the rubble to facilitate recycling, which could be carried out either on-site or off-site. The latter includes transportation, that should be taken into account, when evaluating the total recycling development (Aidonis, D. et. al, 2008).

According to Bertino et al., in their very recent paper, “deconstruction” plays a vital role in the building’s circularity, when it replaces the typical “destruction” or “demolition” method which results in the generation of a substantial amount of waste, although cheaper and faster compared to deconstruction. Deconstruction, or so called as “construction in reverse”, comprises of dismantling the building components in a systematic and selective way, so as to preserve recyclability and reuse of the materials. Benefited from deconstruction, higher levels of construction waste would be available for recycling and reuse compared to the traditional method, which means more materials would be sent back to the life cycle after the building’s operational life is over, that means more circularity would be possible. Moreover, less waste would be sent to the landfill after destruction and less pollution would be generated, which all result in diminishing the environmental impacts caused during a building’s lifecycle (Bertino et al., 2021).

Furthermore, from what was understood in the analysis section of this research thesis, the environmental impacts of the buildings will actually increase, when no recycling or reuse scenario is adopted to deal with the construction materials at the end of their life. This, having in mind the huge share of construction materials in the entire life cycle impacts of the buildings, emphasizes the need to obtain deconstruction or disassembly methods at the end of the building’s life, rather than a conventional demolition in which the materials and components are demolished in a hefty, mixed mass. Reasonably, the financial, environmental and legislative factors have pushed many companies to take the reverse logistics into consideration and adjust their design and planning strategies towards optimizing the recycling (Aidonis, D. et. al, 2008).

Due to the remarkable share of the construction industry in the global GDP, any change in this sector would result in a great effect, in terms of reducing the environmental impacts and energy demand worldwide, thus would allow mitigation of climate change effects to a great extent (Bertino et al., 2021).

The deconstruction or disassembly and separation method of building demolition, is currently substituting the conventional methods, due to the benefits it brings. Above all, the recovery rate of building materials would be boosted and their life cycle would be extended, thanks to this demolition method. Furthermore, other advantages are counted as following:

- Reduction of the construction and demolition waste that needs to be landfilled
- Facilitating the separation of hazardous material from other waste
- Lowering the waste disposal costs
- Promotion of recycling facilities and companies
- Preserving historical or worthy architectural

(Aidonis, D. et. al, 2008).

This topic has dragged a lot of attention from municipalities to develop methods which help cut the amounts of this bulky, heavy type of solid waste, as of the traditional demolition method. The main constituents of the construction waste are materials such as concrete, metals, brick, gypsum, glass and plastics (Aidonis, D. et. al, 2008). This regular composition of construction waste, in the case of the building under study in this research paper, matches the most contributing materials to the environmental impacts that the building envelope comprises of. Accordingly, the materials and components of the Leek Municipal Workshop, which are important to be dismantled or deconstructed, instead of being destructed, would be grouped as shown in the figure below:

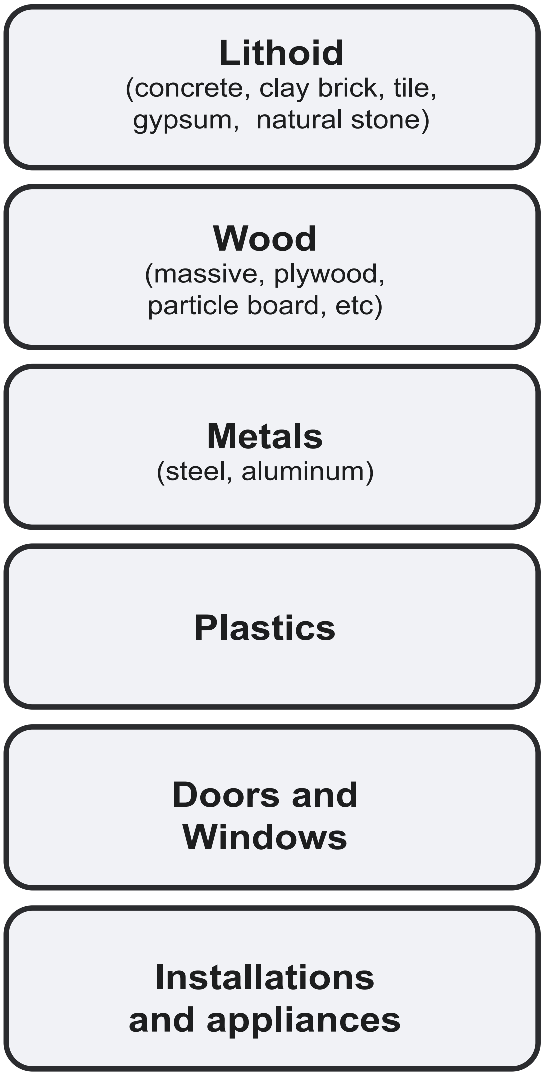


Figure 48 Important materials in the Leek Municipal Workshop building to be recovered after deconstruction, based on their share size in the building material inventory.

5.2 METHODOLOGY PROPOSAL

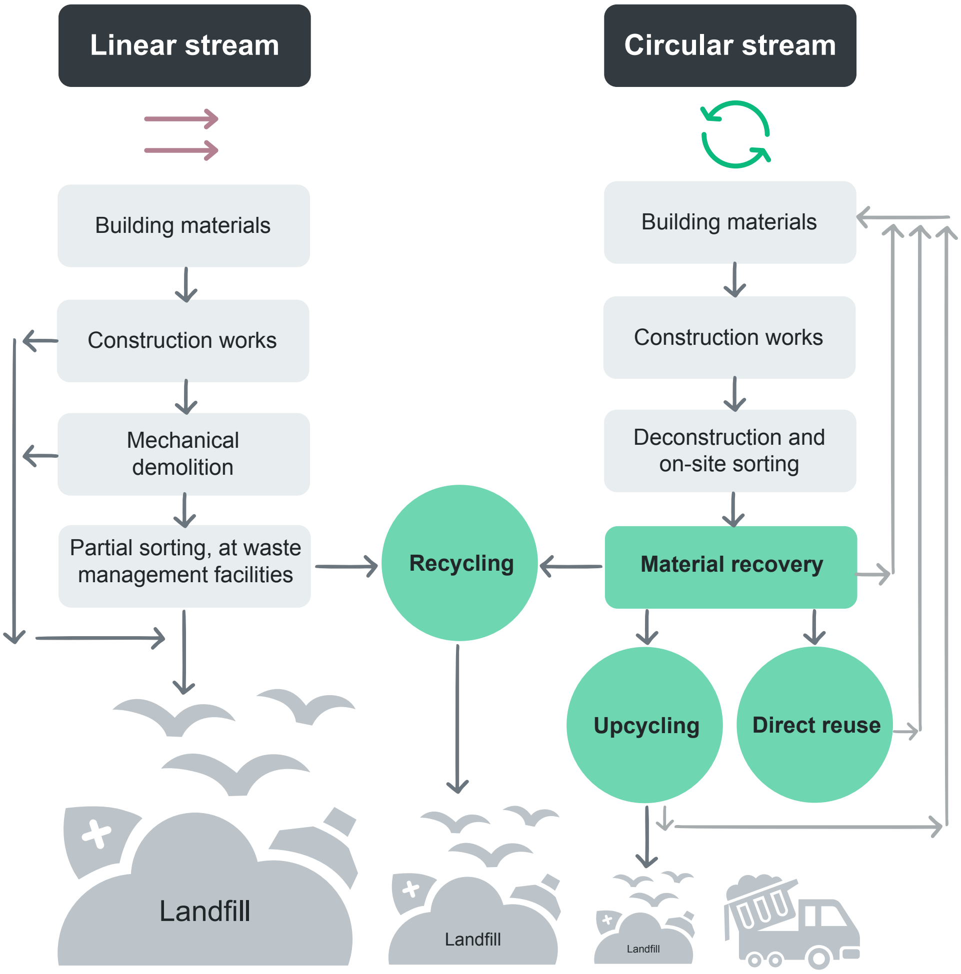


Figure 49 Demolition and deconstruction as building end of life scenarios in a glance. Data retrieved from Placeeconomics, 2021, graph regenerated by author, 2021, Icons from thenounproject.com.

The building of Leek Municipal Workshop has reached its end of operational life, considered as an integrated part of an extensive urban renovation project (see section 1.3). Therefore, bringing down the building is planned by the project team which should preferably be carried out with sustainability and reuse/recycling considerations. In the current section of this research thesis, the proposal of "deconstruction" method will be provided that aims to maximize the material recovery after the building is down.

The proposed method is expected to replace the conventional demolition method in the building under study and also potentially in other neighboring buildings within the project. Following the principles of the BAMB*, the proposal seeks to enhance the materials reuse and recyclability potential.

**BAMB or Buildings As Material Banks project is part of the European Union's Horizon 2020 program and brings 15 parties from 7 European countries together for a unified mission of enabling a systemic shift in the building sector by creating circular solutions in the construction industry. The BAMB project is funded by the European Commission within Horizon 2020, which is the biggest EU Research* *and Innovation program ever founded and aims to create a sustainable economy and growth through driving development in Europe (BAMB, 2016).*

Deconstruction attempts to increase the recyclability of the building materials, and unlike demolition, generates stocks of homogenous materials with minimized damage, thanks to the dedicated time and labor for individual and sequential deconstruction activities (R.Chini & F.Bruening, 2003).

Deconstruction, as explained by the PlaceEconomics, is “The process of dismantling structures component by component in order to harvest materials to be salvaged”. The method not only results in maximizing the material recovery, but also does create numerous job opportunities, reduces the polluting emissions, and keeps the landfills away from being saturated by demolition waste. In addition, deconstruction is a beneficial alternative for the cases in which historical monuments should be conserved (PlaceEconomics, 2021).

Figure 50 Flooring reclaimed during a City of San Antonio Certified Deconstruction Contractor Training, set aside for de-nailing by participants. Placeeconomics, 2021.

Figure 51 Reclaimed doors from the early hours of a City of San Antonio Certified Deconstruction Contractor Training, set aside prior to transfer to a reclaimed materials warehouse. Placeeconomics, 2021.

History:

Deconstruction and reuse of materials of old buildings in new constructions have been executed throughout the history, for the memorial or historical building elements in particular. Examples of this could be found among the historical monuments of the ancient Roman empire and the medieval era.

The triumphal arc of Constantine in Rome, Italy, for instance, was built around the year 315, containing historical elements from the preceding memorials that have previously been dedicated to the emperors Trajan, Hadrian, and Marcus Aurelius. To be more precise, as Bertino et al., 2021 explain, “the frame of the main order, the Corinthian capitals, the shafts in ancient yellow marble, and the bases of the columns are all elements of reuse, affecting a historical period of more than a century, as well as the monumental decorative scheme of the reliefs”. Figure 52, extracted from the same paper, demonstrates the elements that have been demounted from ancestor buildings and assembled to the new one (Bertino et al., 2021).

Moreover, the front tower of the church of Santa Maria Maggiore della Pietrasanta, located in Napoli, Italy, dating back to 10th - 11th century, represents another historical example of building material reuse, dismantled from old buildings. This Romanesque masterpiece, is so called as an architectural “patchwork”, since it carries numerous elements from its predecessors. Huge marbles from Roman to the Middle Ages are visible on the base of the bell tower; additionally, a block of studded marble, an altar, few columns, friezes and beams, as well as blocks of lava stones, which were used as paving material in Roman Ages, and a slab of “ludus latrunculorum”, a popular, chess-like game played by the Roman soldiers are visible (Bertino et al., 2021).

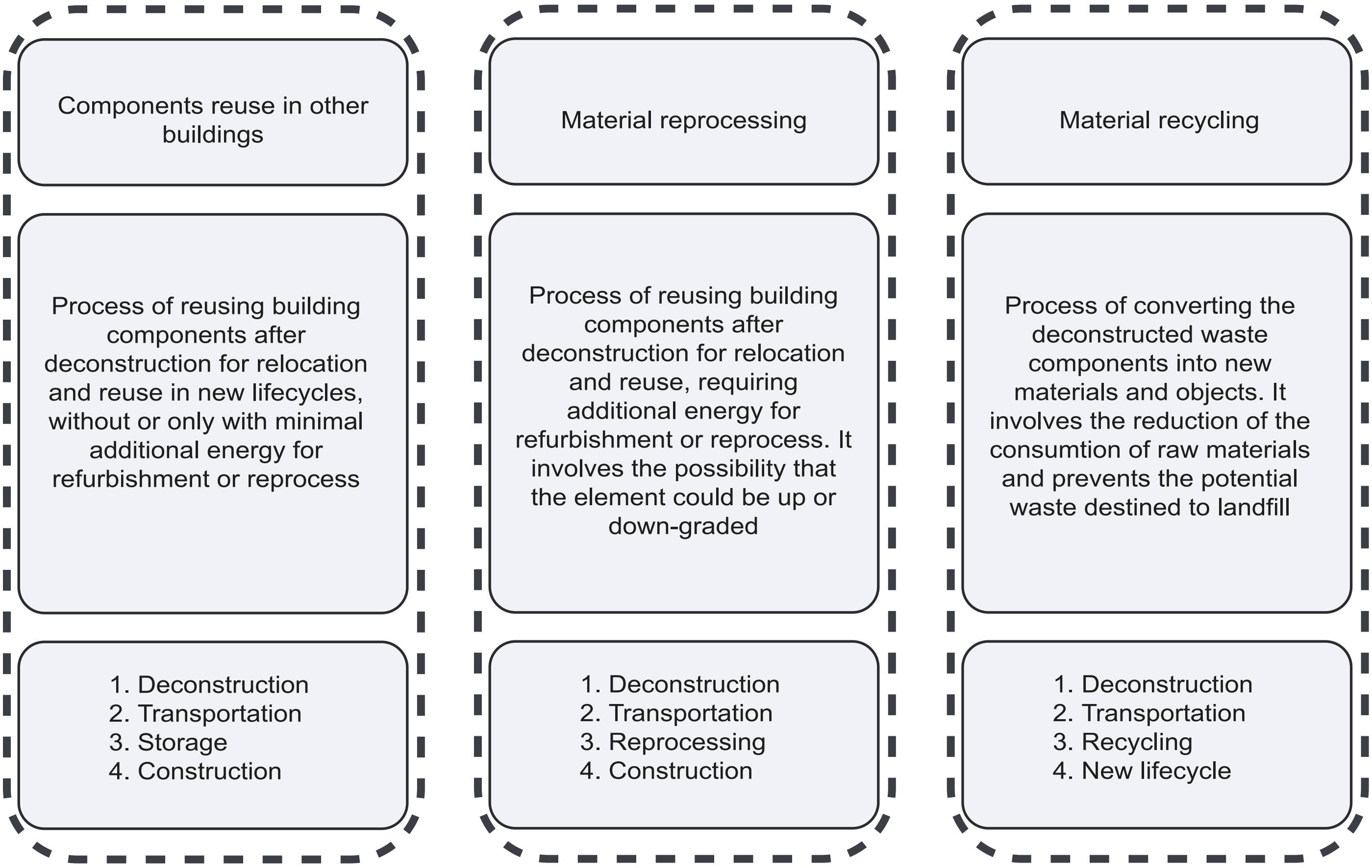
Figure 52 Reused elements of the arch of Constantine, obtained from buildings of previous emperors. Bertino et al., 2021 . Image from www.britannica.com, graph regenerated by author, 2021.

Figure 53 Reused elements in the base (A) and the rear side (B) of the bell tower of Santa Maria Maggiore della Pietrasanta. Bertino et al., 2021 .

Method:

Deconstruction can be executed in different directions. The first one deals with dismantling the building elements or components and reuse them directly in a new construction. Whereas the second and the third direction is the reprocessing of building materials after deconstruction by preparing them for recycling, upcycling or downcycling. An overview of the deconstruction directions is presented in figure 54.

After reviewing various sources of literature including conference papers and scientific articles, a set of recommended steps for deconstruction of a building similar to the type of the building under study are given in the following. Figure 55 displays the major steps of the disassembly, deconstruction and post-deconstruction activities of the building. Extensive description of each step will follow.



Components reuse in other buildings	Material reprocessing	Material recycling
Process of reusing building components after deconstruction for relocation and reuse in new lifecycles, without or only with minimal additional energy for refurbishment or reprocess	Process of reusing building components after deconstruction for relocation and reuse, requiring additional energy for refurbishment or reprocess. It involves the possibility that the element could be up or down-graded	Process of converting the deconstructed waste components into new materials and objects. It involves the reduction of the consumtion of raw materials and prevents the potential waste destined to landfill
1. Deconstruction 2. Transportation 3. Storage 4. Construction	1. Deconstruction 2. Transportation 3. Reprocessing 4. Construction	1. Deconstruction 2. Transportation 3. Recycling 4. New lifecycle

Figure 54 Domain and different directions of deconstruction aiming at recovering building materials and components. Bertino et al., 2021 .

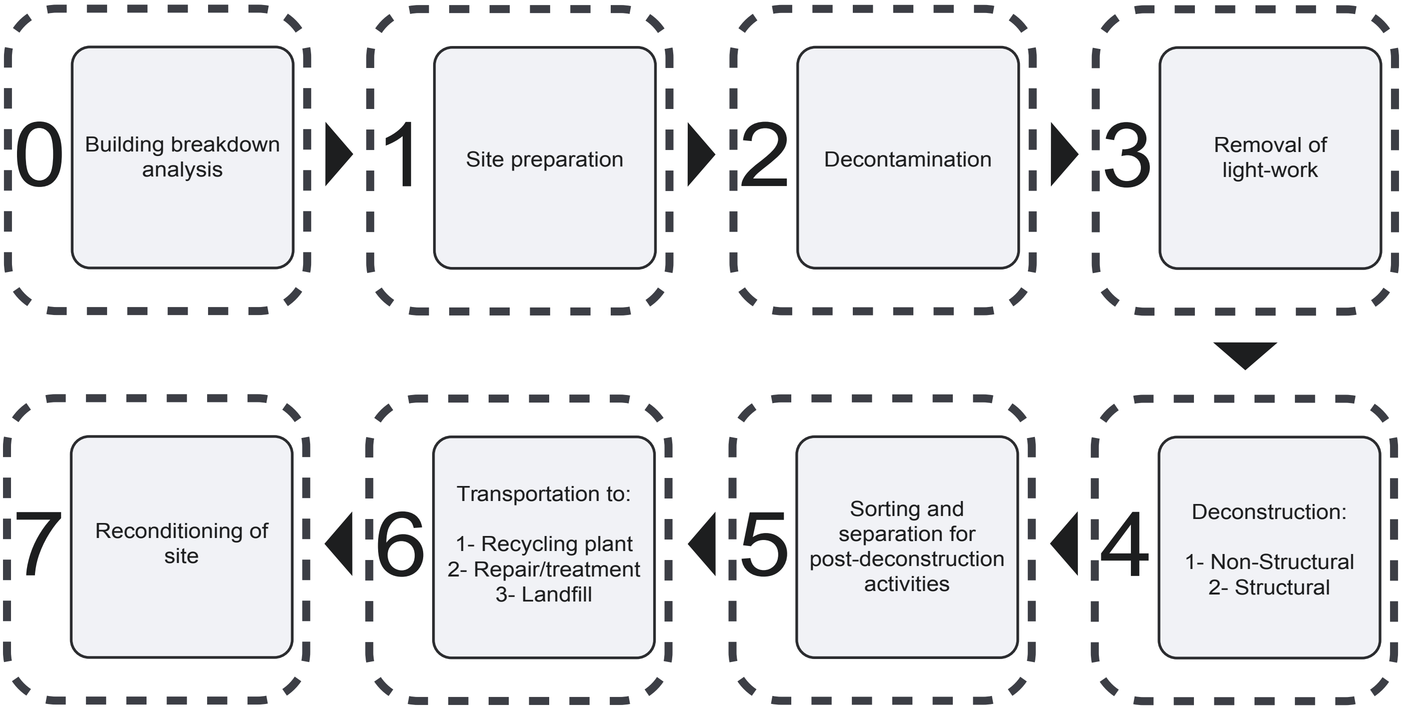


Figure 55 Proposed deconstruction methodology - flowchart of steps 0-7, Author, 2021.

0- Building breakdown analysis and definition

As an initial step before any physical action, breaking down the building in order to analyze and define the individual materials and elements is required; during this step, the building's construction system, load-bearing and non-load bearing elements would be identified and categorized, and the appropriate architectural techniques and procedures for dismantling would be determined (Bertino et al., 2021).

The structural system and load bearing elements of the building under study in this research thesis, have been explained in section 4.2. Masonry walls and horizontal load bearing beams as well as structural elements of the roof are the most significant, in terms of size and mass, elements that constitute the load bearing system of the building. The load of the building is transferred to the strip foundations through load bearing walls. Windows and doors are the other group of the building elements, carrying a huge share in the building envelope. Technical installations are the last group of the components inventoried in the building.

The two categories of doors and windows, and

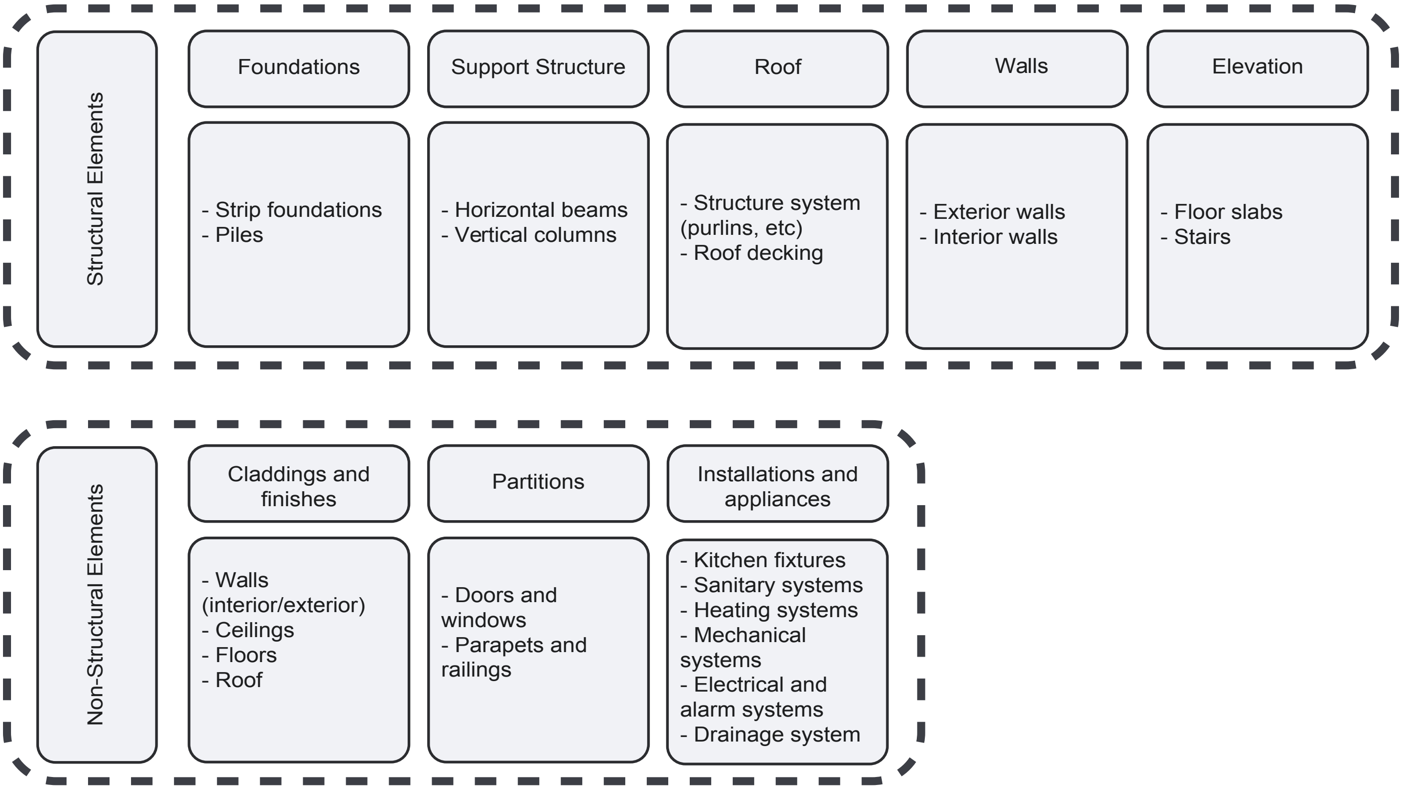


Figure 56 Categorization of elements in the building under study based on structural and non-structural classifications, Author, 2021.

building technical installations are recommended to be dismantled directly and stored with appropriate precautions for further transportation and preparation [repair, treatment] for direct reuse. On-site separation of glass from frames is not forseen.

1- Site preparation

Preparation of the demolition/deconstruction site is an inevitable step in any destruction activity. Organization of the site, temporary installations, pollution risk assessment are among the activities that should be performed at this step. Meanwhile, carrying out a site analysis is advised, in order to discover hidden and potentially dangerous materials and to quantify the materials and components to deal with (Brière et al., n.d.).

2- Decontamination

(not applying to the studied building)

As a preparatory and safety precaution, the contaminated materials, namely asbestos, due to its hazardous characteristics to human health, should be separated with proper procedures and care, before proceeding to any other step (Brière et al., n.d.). However, no asbestos has been detected in the inventory analysis of the Leek Municipal Workshop building, according to the patology report performed by Antea Group, NL.

3- Removal of light work and installations

In this step, all of the electrical and mechanical equipment and installations of the building, either internal or external should be removed and stored separately. The mentioned components are recommended to be dispatched to the relevant recycling/downcycling plant.

4- Structural / non-structural deconstruction

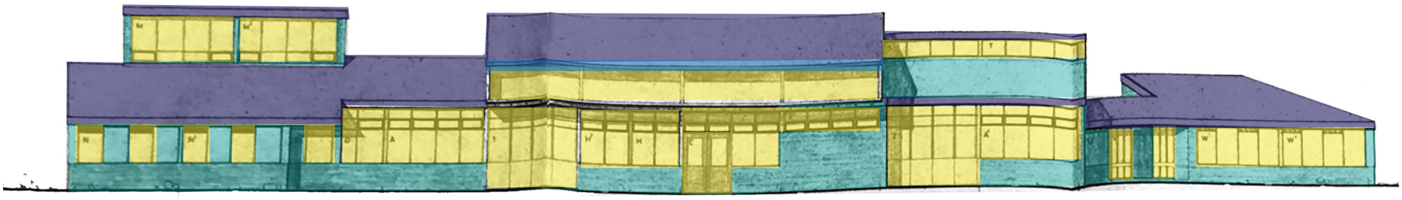
Deconstruction activities should be separated into the two categories of structural and non-structural building elements. The first set of activities, deal with deconstructing the elements which are integrated in the load-bearing and stabilization of the building. It includes beams, columns, roofs, and load bearing walls. Structural deconstruction requires special machinery and equipment as well as appropriate safety precautions (Bertino et al., 2021).

Non-structural deconstruction activities consist of dismantling the building elements which are not integrated in the building system and hence the building stability is not dependent on them. Therefore, demounting such items, is less complex and requires fewer equipment and labor, and could be executed under typical construction site safety procedures and at a shorter time span (Bertino et al., 2021). Doors and windows, technical appliances, floor finishes and wall claddings stand among the non-structural elements group.

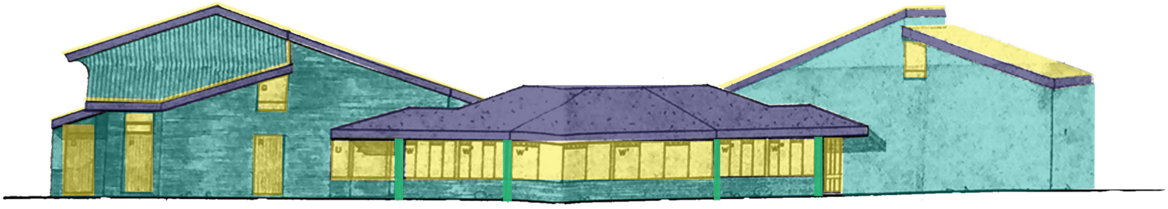
From a sensible and technical perspective, and having practicality considerations in mind, deconstruction of the non-structural elements cannot take place after dismantling the structural elements, due to [un]stability issues of the building under deconstruction (Bertino et al., 2021); deconstructing in a reverse order, would cause the building collapse that comes along with further unwanted issues such as demolition of other elements under the rubble as well as safety threats. For this reason, dismantling of all the non-structural and non-load bearing components of the building in the first stage is recommended before proceeding to the structural deconstruction.

In addition, in order to avoid collapsing, the structural deconstruction should be executed from top to down, starting with roofing elements downwards to the foundations (Bertino et al., 2021).

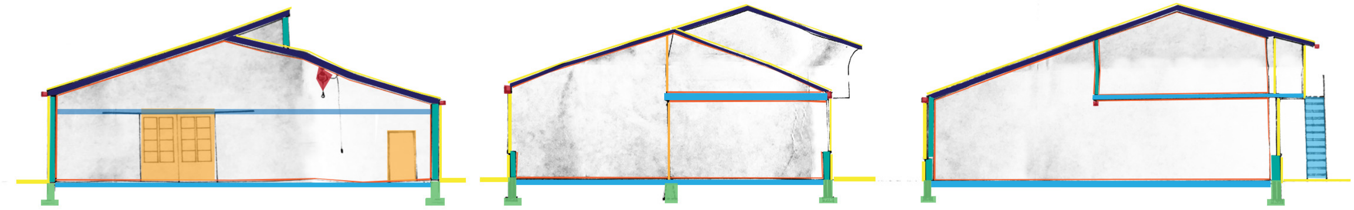
A recommended deconstruction order based on the findings from reviewing various literature is presented in figure 57.



East Elevation



North Elevation



Section B

Section F

Section E

1. Non-Structural

1.1	🟥	Technical installations/light-work (electrical, mechanical, etc.)
1.2	🟧	Finishes, claddings, suspended ceilings, etc.
1.3	🟧	Non-load bearing walls, partitions, interior doors, interior stairs
1.4	🟨	Exterior doors and windows, facade cladding, roof cladding

2. Structural

2.1	🟦	Roof structure
2.2	🟦	Beams (start from upper floor)
2.3	🟦	Floor slabs (start from upper floor), exterior stairs
2.4	🟩	Load-bearing walls interior and exterior (start from upper floor)
2.5	🟩	Columns (start from upper floor)
2.6	🟩	Piers and Foundations

Figure 57 Recommended order of deconstruction for the Leek Municipal Workshop building. Author, 2021.

In the cases similar to the building under study in this research, where the building materials are connected with wet binders such as mortars and adhesives, instead of dry, mechanical joints, deconstruction would be limited, but still possible.

The outcome product of the deconstruction in this case, for elements such as masonry brick walls, would be downcycling or recycling of the building material into filling products, rather than being ready for direct reuse replacing the virgin bricks, although in special situations, if the mortar is separated easily from the brick, reuse option would also be realized. In this case, more time and cost would be consumed and the separated mortar would end up either in landfill or crushed to be used for backfilling purposes. The dismantled brick would also need to undergo cleaning and smoothing treatments which is also costly and probably economically not feasible (Bertino et al., 2021).

5- Sorting and separation (preparation for post-deconstruction activities)

Once the deconstruction is carried out, the dismantled elements need to be sorted and separated based on their type and the composition of materials that they consist of. Therefore, a separation on site as a preparatory step for further individual recycling of the materials is recommended, regardless of which demolition/deconstruction method is adopted to bring down the building. This means, even though the traditional demolition, due to site limitations, project restrictions or financial barriers is still taken up as the end-of-life treatment strategy of the building, the separation of the material categories is strictly recommended, in order to realize further recycling and downcycling of the building materials, by bringing back the rubble into circle and reducing the landfilling amount. Sorting and separation recommendations for the deconstructed elements and materials are as following:

Doors and windows, installations:

Technical appliances and installation devices, as well as doors and windows, are considered – in this research thesis- to be sorted and retained as single elements, which would be transported to the relevant factories that take care of repairing, cleaning and other recovering treatments that are required to enable a direct reuse of these elements. Therefore, a separation of glass from frame for windows, or copper wire from plastic cover for electric cables is not taken into consideration.

Lithoids (concrete, gypsum, ceramic, clay brick):

All of the lithoid (stone) elements demounted from the building are recommended to be crushed and downcycled into secondary aggregate for further use, except the gypsum and stucco elements that are advised to be sent to recycling plant after deconstruction. Consequently, gypsum should be sorted and stored separately from other lithoid elements and be transported to the recycling plant. Other stones, including concrete, ceramics, clay bricks or natural stones are proposed to be crushed on site and stored to be used later as secondary aggregate. Any separated mortar from the building elements would also be crushed and used for backfilling purposes. Protecting the lithoid debris from added humidity is recommended.

Metals (steel, aluminium):

Metals should be separated from each other after the deconstruction, due to unsimilar recycling procedures of different metal types. Steel and aluminum are the only noticeably used metals in the building construction elements and require to be sorted and stored separately after dismantling. The end-of-life scenario for both metals is recommended to be the recycling, and hence, individual metal scraps should be transported separately to the relevant recycling plant.

Separation of Lithoids and metals:

An important step in each demolition or deconstruction method is be the separation of lithoid and metal from each other. The difference between the two building materials, though, lies in their contribution shares to different impacts as well as the recycling procedures; concrete wins the first place to contribute to the global warming, ozone layer depletion, eutrophication, and photo smog, while steel is the largest contributor to energy use and acidification (Blengini, 2009).
For more details on the separation of stones from metals, a glance at a case study in Turin, Italy, analyzed by Blengini, 2019 is provided.

Blengini, in his research focuses on the demolishing of the building and final disposal of the construction waste, based on the LCA results. The study revolves around a residential building which was located in Turin, Italy and underwent a controlled demolition blast in 2004. The demolition of the building was executed through a controlled blasting, having all the safety measures in consideration (Blengini, 2009).

The process was then complemented with more destruction made by hydraulic hammers and shears. The demolition process was followed by a secondary destruction of the rubble on site, during which the building materials were crushed into smaller pieces, and a sorting and separation, using diesel-hydraulic equipment, in order to sort and prepare the demolition debris for disposal.

The execution of the on-site lithoid rubble recycling lasted 40 days, and was performed with particular crushing machinery equipped with jaw crusher and magnetic separator (Blengini, 2009).

Following the adopted demolition [and not deconstruction] method, the waste was categorized into lithoid and metal materials, excluding doors and windows, as they were dismantled prior to the blasting, hence excluded from the system boundary. After measuring the quantities of the on-site re-demolished rubble and records of transportation, it was found out that 99% of the lithoid category was recycled into secondary aggregate, available for reuse as infilling materials (Blengini, 2009).

The metal fraction, on the other side, was partially recycled on site and separated from the lithoid pieces, using the magnetic system, and was then sent to the steel production factory to be recycled into reinforcing steel bars (Blengini, 2009).

The quality contrast between the recycled lithoid and metal material categories is notable; the lithoid debris demotes in classification, from high quality concrete, ceramic, etc. to secondary aggregate material; whereas the steel scrap can always be retrieved back to the production plant, where it can get recycled into steel rebars, and the new quality normally equals the quality of the virgin product. According to the literature, the mass yield of recycling the steel scrap reaches above 93% (Blengini, 2009).

In the case of the Leek Municipal Workshop, separation of metals from stones after deconstruction is recommended; the demounted concrete elements are desired to be crushed and downcycled into aggregate. Though, after the crushing, the metal reinforcement should be separated from the crushed stone. Thus, an on-site crushing of the dismantled concrete elements followed by an on-site magnetic separation of the rebars is strictly recommended, before transportation of the elements to recycling factories.

Wood:

Wooden elements have a remarkable share in the materials used in the Workshop building. they come in different formats and with [probably] various installation techniques and joints. Nailing and interlocking joints provide a good degree of deconstructability and consequently an acceptable quality of dismantled wood to be reused directly as a secondary element. But the wet adhesives face the final deconstruction product with quality problems.

In addition, the pathology report of the building, carried out by Antea Group, NL, reveals poor quality condition of the wooden elements at the current status. The defects range from wood rot, erosion, weathering, siltation and abrasion. Therefore, material reuse or recycling is \ not advised. Instead, wood incineration for energy recovery is recommended as the end-of-life treatment scenario of the wooden elements in the building.

Nevertheless, all the dismantled wooden pieces should be sorted and stocked separately from the rest of the materials and be transported to the nearest incineration plant. An immaculate compilation of the wood debris free from added humidity, other dirt or materials before sending to incineration is required.

Plastics:

Even though the amount of plastic mass in the building under study is relatively small, this material category should not be eliminated from separation, sorting and recycling procedure. Plastic elements are recommended to be separated and sent directly to plastic recycling factories. A plastic incineration for energy recovery, is due to pollution problems and small amount of plastic stock in the building not recommended.

6- Transportation

The sorted materials and elements would be next dispatched to the nearest treatment plants for the purposes of preparation and treatment for direct reuse, recycling or downcycling. The remaining materials that are excluded from sustainable end-of-life scenarios due to existing restrictions or wastage and difficulties during deconstruction, should be transported to the nearest landfill. Transportation means and details is be defined per each material group, according to the adopted end-of-life treatment concept. Choosing the treatment plants at the closest proximity is recommended in order to cut down on fuel consumption and pollution.

7- Reconditioning of site

Similar to any other demolition project, the site should be cleared and reconditioned after the end of the deconstruction and relevant on-site post-deconstruction activities (such as lithoid crushing or magnetic metal separation) activities. Any temporary installation, machinery and equipment should be removed at this step (Brière et al., n.d.).

Figure 58 Some of the reclaimed materials demounted during the deconstruction contractor training workshop, City of San Antonio Certified Deconstruction in 2019. Placeeconomics, 2021.

Figure 59 A portion of the reclaimed flooring and shiplap, ready to be transported off site from the San Antonio City's second Certified Deconstruction Contractor Training. Placeeconomics, 2021.

Remarks:

Despite the remarkable share of the building's use-phase in contribution to the environmental impacts compare to the pre-use and end-of-life phases, a proper planning and proposal of alternative scenarios would be beneficial. The reason is that the appropriate planning of these two phases, influences the impacts that would be caused during the operation phase. For instance, adopting specific materials or alternative design approaches would affect the energy consumption pattern during the use-phase (Blengini, 2009). On the other hand, a selection of building materials that could be easily recycled as well as the building components which could be easily disassembled and reused, would result in improved end-of-life impacts, hence affecting the building's entire life cycle impacts. Moreover, maximizing the building rubble recycling, brings benefits to the landfilling processes, as it decreases the need for landfilling, which is a noticeable issue in many large cities. It also has economic benefits for the project developers, since the costs would be reduced by avoiding the landfilling taxes and the relevant costs that would be replaced by smaller expenses which would be paid to the private companies who will be in charge of the recycling procedures (Blengini, 2009). Construction and building industry, due to its large size in contribution to the global economy and environmental impacts, is a predominant sector in transition from the linear to the circular economy. When appropriate methods are taken into consideration by the decision makers, buildings can be effective players in contribution to resource efficiency, enhancement of energy demand through reduction of consumption during their entire life, as well as materials sustainability, less waste generation and more recycling (Bertino et al., 2021).

Criteria	Demolition	Non-Structural Deconstruction	Structural Deconstruction
Definition	Arbitrary destruction of building in order to quickly clear the construction site	Removal of building components not affecting the structural integrity of the building	Removal of building components completely integrated in the building and with structural function
Time	Few days	Few days	Days or weeks
Cost	Low	Medium	High
Equipment	Expertise required for cranes, excavators, and wrecking balls	Simple tools required. Special expertise is usually not required	High range of tools and equipment required. Special expertise could be required
Safety conditions	High	Standard	High
Degree of deconstructiveness	None	High	Variable

Table 9 Comparison between conventional demolition and alternative deconstruction in its two phases. Bertino et al., 2021.

Deconstruction and demolition as two alternatives of buildings end-of-life concept individual characteristics, with similarities and contrasts between them. An overall comparison of the two methods, gathered by Bertino et al., 2021, is given in table 9.

Barriers:

Deconstruction method requires special logistics and enough time. Therefore, the project planners should outline the deconstruction activities with the necessary equipment and at a proper timing. Deconstruction is a labor extensive activity and according to R.Chini and F.Bruening, it is estimated to take at-least two times and up to ten times as long as the normal demolition. However, the exact elapsed time depends on the size of the building. Also, seeking service from experienced and qualified contractors with trained manpower is recommended (R.Chini & F.Bruening, 2003).

Despite deconstruction brings many benefits with it, currently, very few number of buildings are designed for deconstruction. This reflects the existing barriers in deconstruction methodologies.

As Bertino et al., 2021 report, at the moment only around 1% of the buildings are fully demountable; this comes from the conventional building and design strategies that consider the building as a permanent element, free from proper arrangements for future dismantling. Inevitably, development of tools and techniques for dismantling the existing buildings is currently at an early stage. Also, there is a lack of concrete, clear guidelines for designers and planners (Bertino et al., 2021). Accordingly, improved design principles adapted to deconstruction and dismantling goals, such as Design for Disassembly and Design for Adaptability are recommended to become widespread among designers and planners.

Adopting such design principles, would maximize the degree of deconstuctability. Moreover, the buildings vary enormously in their construction type and age. Such differences, that come along with heterogenous material combinations and structure types. This faces defining any deconstruction strategy with complications, since each individual material or structure has a certain different level of deconstructiveness and requires a different approach. Hence, recognizing such differences within the building stock and determining an appropriate deconstruction program that is environmentally and economically feasible and affordable, needs remarkable efforts (Bertino et al., 2021).

Deconstruction of the Leek Municipal Workshop, would not ideally result in direct reuse and high quality recycling of the building materials, since the current situation of the majority of the inventoried materials is reported to be defect or damaged. Hence, downcycling is the largest outcome of the deconstruction of this building. However, it could be still possible that more materials undergo a proper cleaning and treatment process after deconstruction and meet the quality standards of being reused in new construction works [at lower classes].

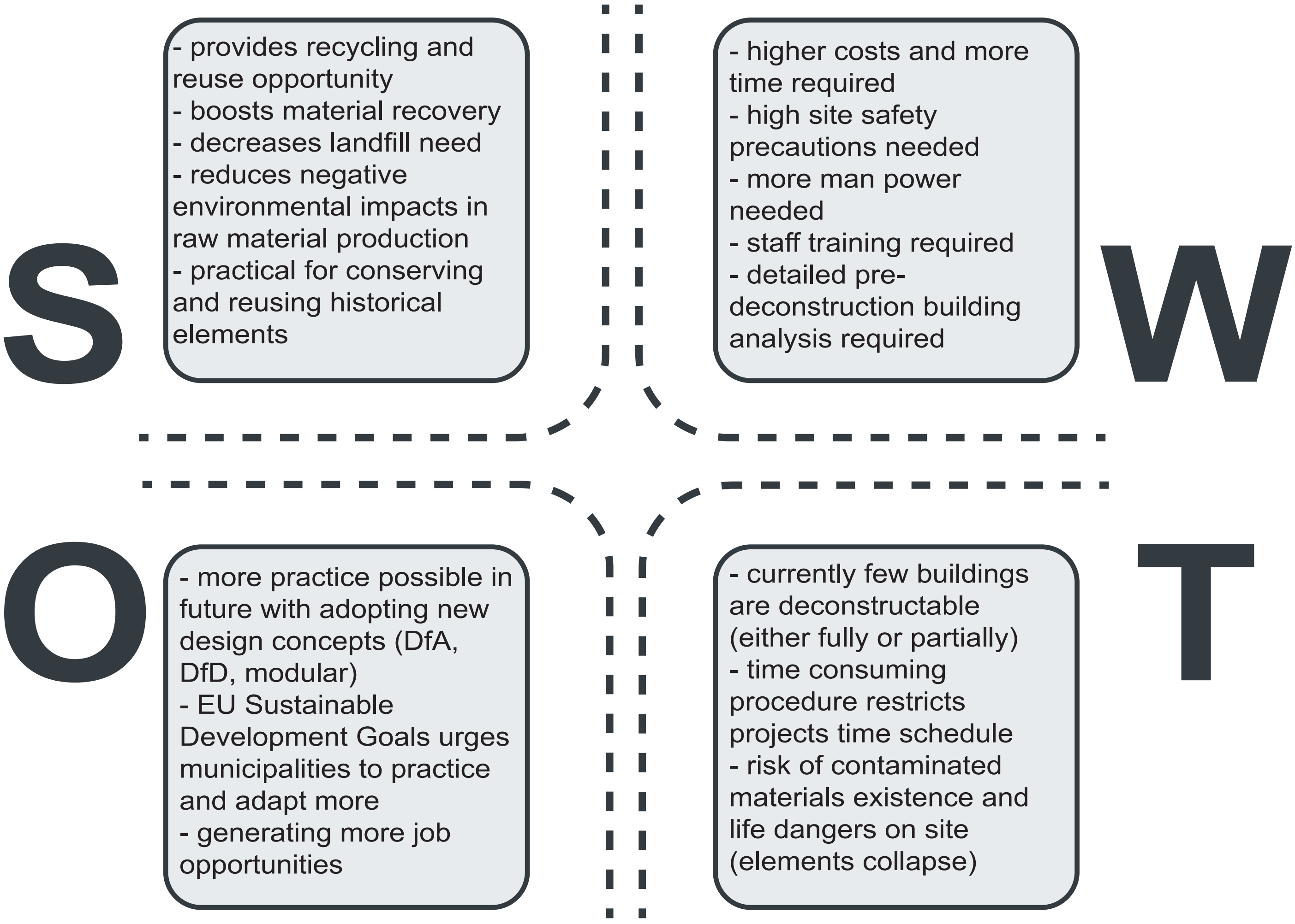
A categorization of the materials and components of the building under study, grouped per current health and degree of damage based on the pathology report, as well as the proposed EOL scenario with deconstruction and post-deconstruction concept is provided in table 10.

Although the costs of deconstruction are higher compared to that of conventional demolition, they can vary depending on the size, location and complexity of the project. The largest share of costs and elapsed time goes to the structural deconstruction. This stems from extensive labor costs and hardship of work. However, several environmental benefits are resulted from the process. Cutting down the amount of generated construction and demolition waste, and decreasing the need for landfilling on one hand, reducing the building material supply (including all the stages from raw material extraction to manufacturing and delivery to site) through re-placing [either fully or partially] the virgin materials with recycled materials (reuse) on the oth-er hand, are the most valuable advantages of deconstruction and disassembly approaches. Preservation and reuse possibility of historical monuments are the other profit of this approach. Deconstruction requires technically trained manpower and specialist contractors; though it cre-ates more job opportunities in the building and construction industry. From a socio-economic perspective, adopting deconstruction method by municipalities, small businesses and vocational training opportunities would develop in the cities (Bertino et al., 2021 and Author, 2021).

A SWOT analysis of the proposed methodology, in order to visualize the strengths, weak-nesses, opportunities and threats will follow.

material/ component	current quality/ defficiency	intensity	EOL process	demolition method proposed
concrete cladding	erosion, weathering	minor	crushing to aggregate	deconstruction + crushing on-site
concrete elements (foundations)	erosion, weathering	minor	crushing to aggregate	deconstruction + crushing on-site
steel elements (others)	corrosion	serious to severe	recycling	deconstruction + magnetic separation + send to recycling plant
steel elements (structure)	corrosion	moderate	recycling	deconstruction + magnetic separation + send to recycling plant
steel elements (concrete rebar)	corrosion	moderate	recycling	deconstruction + magnetic separation + send to recycling plant
bitumen layers	abrasion	serious	recycling/landfill	deconstruction + send to recycling plant or landfill depending on the resulted situation
masonary clay bricks	erosion, weathering, siltation	serious to severe	crushing to subbase aggregate	deconstruction + crushing on-site
mortar, cement mortar, tile adhesives	dirt, sediment, discoloration, cracks	serious	curshing for backfill use/ landfill	deconstruction + crushing on-site
plywood	abrasion, wood rot	serious to severe	wood incineration	deconstruction + send to incineration plant
massive wood	erosion, weathering, siltation	serious	wood incineration	deconstruction + send to incineration plant
wood elements (structure+others)	erosion, weathering, siltation	serious	wood incineration	deconstruction + send to incineration plant
particle board	abrasion, wood rot	serious	wood incineration	deconstruction + send to incineration plant
plasterboards	dirt, sediment, discoloration, cracks	moderate	recycling	deconstruction + send to incineration plant
stucco	cracks	serious	recycling	deconstruction + send to recycling plant
ceramics	damaged	serious	crushing to subbase aggregate	deconstruction + crushing on-site
aluminium elements	erosion, weathering, siltation, abrasion	serious	recycling	deconstruction + send to recycling plant
wood wool panels	erosion, weathering	serious	wood incineration/ landfill	deconstruction + send to incineration plant or landfill depending on the resulted situation
mineral fiber boards	erosion, weathering	serious	recycling/landfill	deconstruction + send to recycling plant or landfill depending on the resulted situation
linoleoum carpets	erosion, weathering, dirt	serious	recycling	deconstruction + send to recycling plant
natural stone	erosion, weathering, siltation	moderate	crushing to aggregate	deconstruction + crushing on-site
sanitary objects (porcelaind & steel)	> 75% theoretical lifespan	minor	reuse	deconstruction + send to repair/treatment plant for probable reuse
wooden doors and windows	damamaged frames	severe	reuse	deconstruction + send to repair/treatment plant for probable reuse
metal doors and windows	damamaged frames	severe	reuse	deconstruction + send to repair/treatment plant for probable reuse
technical installations	> 75% theoretical lifespan	severe	reuse	deconstruction + send to repair/treatment plant for probable reuse

Table 10 The building materials and components grouped per current health situation, degree of damage, EOL scenario, deconstruction and post-deconstruction concept. Author, 2021.



S

- provides recycling and reuse opportunity
- boosts material recovery
- decreases landfill need
- reduces negative environmental impacts in raw material production
- practical for conserving and reusing historical elements

W

- higher costs and more time required
- high site safety precautions needed
- more man power needed
- staff training required
- detailed pre-deconstruction building analysis required

O

- more practice possible in future with adopting new design concepts (DfA, DfD, modular)
- EU Sustainable Development Goals urges municipalities to practice and adapt more
- generating more job opportunities

T

- currently few buildings are deconstructable (either fully or partially)
- time consuming procedure restricts projects time schedule
- risk of contaminated materials existence and life dangers on site (elements collapse)

Figure 60 SWOT analysis for Deconsutruction as the building end of life concept. Author, 2021.

6 CONCLUSION

The comparison results of both LCA and building circularity of the Leek municipal workshop building, explain the noticeable role of circular [recycling or reuse] end-of-life scenarios for municipal buildings. In other words, the environmental impacts of the building and its circularity score alter remarkably when landfilling replaces the recycling or reuse alternatives to deal with the materials when the building's life is over. Thus, it could be concluded that:

- The project planners and designers are recommended to adopt circularity principles, as well as the concepts of design for disassembly and design for adaptability in the initial planning phases of the buildings in order to eliminate or reduce the environmental impacts and the carbon footprint of their construction projects

- The decision makers and project managers are recommended to take proper demolition and disassembly methods for destruction of the old buildings, that, like the building studied in this research, have passed the planning and design phase, in order to maximize the material recovery after demolition and reduce material wastage during and after demolition.

The objective of the above concluded points would be the reduction of the use of virgin materials so as to decrease the need for raw materials and energy/carbon extensive material manufacturing procedures. In other words, since the A1-A3 stages (cradle to gate) are the ones that cause the largest impacts on the environment during the entire life cycle of the building, lowering any parameters within these stages, such as reduction in use of virgin materials, would make a remarkable change on the entire impacts caused by a building during its life cycle.

In the journey of transition from linear to circular economy, in which materials are recycled and reused instead of going only through the circle of manufacturing, use and discarding, deconstruction is a key driver. Replacing deconstruction with demolition, allows cities to recover and leverage the existing strengths and step towards sustainability in economy, environment and social aspects (PlaceEconomics, 2021).

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