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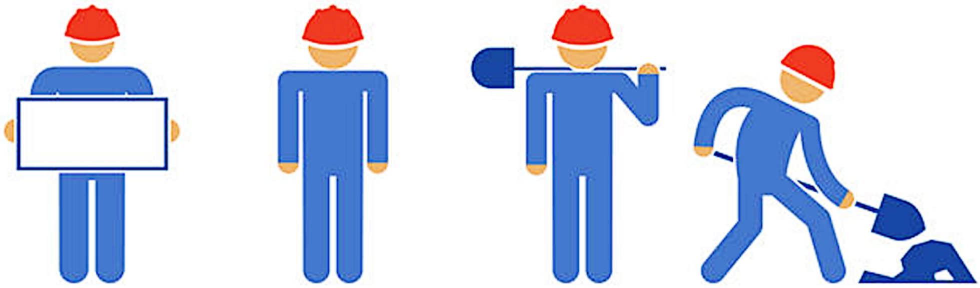

The future of concrete recycling

An integrated life cycle environmental and cost analysis on the hotspots to improve the demolition and recycling practices across Europe

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Master Thesis Project

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An integrated life cycle environmental and cost analysis on the hotspots to improve the demolition and recycling practices across the Europe

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Abstract

Building construction is a material-intensive process known for depleting natural resources, mainly gravel and sand, used in concrete production. At the same time, building demolition generates large amounts of construction and demolition waste (CDW), primarily consisting of end-of-life (EOL) concrete, a significant waste flow occurring in Europe's construction sector. The potential to deal with waste management and the uprising demand for new concrete in construction lies within circular economy-based solutions applied throughout the building's lifecycle. Steering in this direction, the European Union is endorsing a circular economy strategy that aims to utilize EOL concrete derived from CDW to produce new concrete and thus minimize virgin material inputs. These efforts have not been translated to a uniform framework for Europe, where practices, regulations for waste management, and market acceptance for secondary raw materials differ among member countries. In this project, different types of pre-demolition audits, demolition, and waste processing methods for EOL concrete are compared, showcasing the status quo across the EU and the Dutch case study, which portrays innovations that can shape the future of concrete recycling. An integrated LCA and LCC framework is applied from the demolition stage to waste processing and the production of materials for new construction to capture potential environmental and economic benefits and drawbacks at the end-of-life stage (EOL) of the building. The results showcase the pivotal role of BIM-supported pre-demolition audits in combination with selective demolition with benefits that include lower quantity of generated waste allocated to treatment and more components available for reuse. Finally, LIBS, a quality assurance tool for recycled aggregates, shows great potential in supporting a market for secondary raw materials in Europe.

Keywords: CDW, EOL concrete, circular economy, secondary raw materials, pre-demolition audit, selective demolition, LIBS, LCA, LCC

Acknowledgments

After a year of working on this project, I can confidently say it was one of the most formative experiences of my academic life so far. Starting in September 2021, when we first discussed the topic with Dr Mingming Hu and Marc van der Meide, I was given the opportunity to work on a real case study and ongoing project arising from the ICEBERG research program.

During our work together, Dr Hu provided honest feedback that genuinely challenged me personally and academically while shaping my approach toward my thesis project and its scientific contribution. Despite moments of disappointment, with her constant support and guidance, I overcame every doubt and obstacle. Now, I can finally say that I feel satisfied with the result of my work, and I appreciate the journey of getting to this point, despite the hurdles. I sincerely thank Dr Hu for making me see the bigger picture instead of focusing merely on completing tasks. I will always be grateful for this enriching learning experience.

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Declaration

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All appendices were submitted separately as Excel files.

List of Abbreviations

ADR	Advanced Dry Recovery
BAU	Business As Usual
BP	Best Practices
FP	Future Practices
CDW	Construction and Demolition Waste
Circular Economy	CE
C2CA	Advanced Technologies for the Production of Cement and Clean Aggregates from Construction and Demolition Waste
EOL	End-of-Life
EU	European Union
EU MS	EU Member States
HAS	Heating air and classification system
ICEBERG	Innovative Circular Economy Based solutions demonstrating the Efficient recovery of valuable material Resources from the Generation of representative End-of-Life building materials
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LIBS	Laser-Induced Breakdown Spectroscopy
GHG	Greenhouse gas emissions
BIM	Building Information Modeling
WFD	Waste Framework Directive

1. Introduction

Concrete is an engineered material made from sand, gravel, water, and cement. It is the predominant building material worldwide due to its remarkable mechanical properties, adaptability, and affordability (Meyer, 2009). However, it is associated with the depletion of natural resources as almost 50 billion tons of sand and gravel are allocated to concrete production for various construction projects yearly (Bonoli et al., 2021). In Europe, the raw materials used as aggregates for concrete production reached 2.7 billion tons annually (de Andrade Salgado & de Andrade Silva, 2022).

At the same time, end-of-life concrete is the most significant component found in the stony fraction of construction and demolition waste (CDW), which adds up to a billion tons or 1/3 of the total waste generated in Europe (Bonoli et al., 2021). Therefore, the construction sector is dealing simultaneously with two problems related to concrete; the demand for natural aggregates for its production and the need to manage it in the form of waste from demolition works.

This situation presented the opportunity for an inclusive solution by using the recycled aggregates from CDW to substitute natural aggregates in new concrete and thus minimize resource consumption while reducing waste from demolition works (de Andrade Salgado & de Andrade Silva, 2022) according to circular economy principles.

The European Union has set forth goals for the construction sector within its New Green Deal to facilitate the green transition and carbon neutrality by 2050. In that respect, the Circular Economy Action plan was endorsed in 2020 to support the CDW minimization by preventing, reusing, and improving recycling to produce high-quality secondary raw materials. Despite steering in this direction, the EU has yet to adopt a uniform framework for all European countries. Technical challenges, market conditions, and the unwillingness of the construction sector to embrace secondary raw materials are drawbacks hampering the uptake of a circular economy.

In recent years, multiple projects have been developed under EU funding to address these issues. Among them is ICEBERG, a project that aims to develop innovative recycling systems and technologies that will utilize CDW to produce high-value recovered materials. This will be facilitated by six circular case studies in different countries, including the Netherlands, where the case study on circular concrete will take place. Learning from the Dutch case study, this project aims to assess how state-of-the-art circular solutions compare with the average CDW management practices across Europe in environmental and economic terms and explore the possible benefits of their adoption on a European level.

1.1 Concrete as a structural material: components & properties

“Concrete is the fundamental building block of our urbanizing world” (Habert et al., 2020).

The word concrete is an adjective derived from the Latin participle concrētus, describing a condensed or hardened substance and literally means “grown together.” Living up to his name, concrete has been and remains the prevailing structural material used extensively worldwide (Brunauer & Copeland, 1964; Mehta & Monteiro, 2014), and buildings, transportation, power, and water systems all rely upon concrete (Habert et al., 2020). The reasons supporting concrete’s dominance in the construction world are its properties, including the resistance to water, easy formation into different shapes and sizes, no corrosion or need for surface treatment, fire resistance, and its availability in combination with low economic cost (Mehta & Monteiro, 2014).

Concrete is a composite material whose primary constituents are aggregates, air, sand, water, and cement. According to Mehta & Monteiro (2014), there are two types of aggregates used in concrete production classified by size; particles larger than 4mm are coarse aggregates such as gravel or crushed stones, and particles smaller than 4mm but larger than 75 μm are fine aggregates usually referred to as sand.

Generally, concrete can be categorized as normal, lightweight, or heavyweight concrete depending on the unit weight. Other types of concrete include high-density, air-entrained, asphalt, precast and ready-mix concrete. Commonly, normal-weight concrete weighs 2400 kg/m3 and is used for structural applications. Another classification can be based on compressive strength with low, moderate, and high-strength concrete with moderate strength ranging from 20-40 MPA. Each of the categories mentioned above has different mixtures and compositions of the constituent materials, as presented in Table 1:

Table 1. Types of concrete based on compressive strength and their material composition, an adaptation from Mehta& Monteiro (2014)

	Low strength	**Moderate strength**	**High strength**
	Kg/m^3		
Cement	255	356	510
Water	178	178	178
Fine aggregates	801	848	890
Coarse aggregates	1169	1032	872
Cement paste proportion (% mass)	18	22.1	28.1
Strength (MPa)	18	30	60

The standard mixture for concrete is about 10% cement, 20% air and water, 30% sand, and 40% aggregates, and the average composition, according to Evangelista & de Brito (2007), is presented in Table 2:

Table 2. Average composition for concrete, adaptation from Evangelista & de Brito (2007)

Materials	Amount	Unit
Cement	362	Kg/m^3
Sand	615	
Coarse aggregates	1195	
Water	188	L/m^3

In addition, different admixtures (e.g., chemical, water, air-entraining, minerals) can be added before or during the mixing of concrete to modify characteristics such as hardening, surface tension, thermal cracking, durability to weather conditions, etc. (Mehta & Monteiro, 2014).

In addition, concrete has excellent compressive strength. However, when in tension, the concrete elements might fail abruptly when a crack is formed. To prevent that, steel bars are used as reinforcement in regular concrete to delay cracks when the concrete is under tension (Wight, 2016). Among the different concrete types, reinforced concrete is the most popular in construction, and it is used in all kinds of construction, from buildings and bridges to wind turbine foundations (Wight, 2016).

1.2 Resources for concrete production & related environmental issues

The consumption of concrete is growing along with the increased population and income, resulting in a direct material resource demand of 30 Gt yearly for its production (Miller & Moore, 2020). According to Habert et al. (2020), the annual concrete production is immense and amounts to 10 billion m^3. Unavoidably, it is associated with several detrimental environmental effects related to its components, namely the regional resource scarcity of aggregates, greenhouse gas and air pollutant emissions from cement production, and health issues concerning the use, management, and consumption of water.

1.2.1 Aggregates

Despite the common perception that sand and gravel are abundant on Earth, these aggregates are extracted in the most significant volumes among raw materials, surpassing fossil fuels (Bendixen et al., 2019) and with a faster pace than their natural renewal rate (Peduzzi, 2014). The extraction of aggregates can be correlated with cement production that is thoroughly documented and thus indirectly estimated. In that respect, the analogy of sand and gravel to cement is 7:1. According to the European Cement Association, the EU-28 produced 182.1 million tons of cement that, would amount to approximately 1.27 billion tons of aggregates.

This amount is significant and cannot be extracted without raising regional and global scarcity issues and causing several environmental impacts. Specifically for sand, it is widely considered a common-pool resource. Thus, its mining is not regulated, resulting in sand appropriation, illegal mining, and trade that causes pressure on the available deposits (Torres et al., 2017).

Besides mining alongside rivers, floodplain quarries, and shallow riverbeds (Bendixen et al., 2019), the reduction of inland resources led to mining marine and coastal aggregates that require additional processing to remove salt and avoid corrosion. Additionally, the demand for aggregates combined with intensive construction activities increases local pressure in areas near urban centers (Habert et al., 2020). However, the high operational, economic cost, and undesirability of sand mines and quarries near cities might increase transportation distances of materials from other areas or countries.

As a result, the fast-paced extraction of large quantities of aggregates is related to global sustainability challenges. Moreover, extracting marine aggregates from the sea bottom affects biodiversity by destroying the ecosystem and its organisms (Peduzzi, 2014). Similarly, in rivers, removing sediment can lower the water table and lead to extreme weather events such as frequent droughts and dry-up of rivers, thus endangering the water supply (Peduzzi, 2014; Myers et al., 2000). According to Peduzzi (2014), the extraction of aggregates can impact biodiversity by upsetting ecosystems, causing land loss and landscape change via coastal erosion, affecting hydrological functions by altering water flows and currents, and contributing to climate change via transport emissions.

1.2.2 Cement

Concerning anthropogenic GHG emissions and energy demand, concrete production accounts for 8% and 3%, respectively, on a global scale (Miller & Moore, 2020). However, the point of attention within concrete manufacturing is cement production, which has the dominant share of a minimum of 70% of GHG emissions (Habert et al., 2020), along with significant health impacts.

Based on its composition, cement is classified into five types that can be further categorized into three grades depending on compression strength after casting, according to EN 197, 2011 (Cruz Juarez & Finnegan, 2021). CEM I is the type containing 95% of Portland cement, and it is the most commonly used cement in concrete. The primary raw materials used in its production are limestone, clay, sand, and ores. According to EEA, the demand for raw materials is approximately 1,6 tons for one-ton clinker cement. The production of cement is carried out in four phases; starting with the extraction and initial processing of raw material, pyro-process for the production of clinker that is then blended and grinded to the cement and completed by storing, packaging, and transporting the final product (Berdowski et al., 2019)

Apart from being a highly energy-intensive industry, ranking third in energy consumption worldwide and accounting for 7% of energy use in the industry (Cruz Juarez & Finnegan, 2021), it is also significantly polluting. In that respect, a ton of CO_2 is emitted for each ton of cement being produced, adding up to almost 10% of the total CO_2 released worldwide (Meyer, 2009).

These primary emissions are to air, resulting from the kilning phase and the calcination of limestone. In addition, air pollutants, including particulate matter (e.g., PM10, PM2.5) from raw material acquisition, storing, and managing materials added to cement, are known for their effects on human health, including lung cancer, and pulmonary disease, etc. (Habert et al., 2020). According to the World Business Council for Sustainable Development predictions, cement production will continue to rise by 12-23% by 2050 (Cruz Juarez & Finnegan, 2021; WBCSD, 2018).

1.2.3 Water

The primary research focus on the environmental issues related to concrete production is raw materials consumption and GHG emissions, as described in the previous sections. However, water is a significant component in concrete production, and its consumption is equivalent by mass to cement (Habert et. al., 2020; Miller et al., 2016). Nevertheless, the highest water consumption of concrete and cement production is attributed to the quarrying, washing, and crushing of primary materials (Habert et al., 2020).

Furthermore, the shift from the river to crushed aggregates is accompanied by higher water consumption allocated to their treatment to ensure performance quality standards and avoid dust emissions. In addition, global water use in concrete production is a point of attention, especially for rapidly urbanizing regions. Specifically, for concrete production, water withdrawals accounted for 9% of industrial water in 2012; ¾ of water demand is expected in areas where natural deposits are depleted (Miller et al., 2018).

1.3 Concrete in CDW and its management

The construction sector is not only associated with the high consumption of raw materials but also with increased waste generation (Gebremariam et al., 2020). The European Union is among the top 3 CDW generators, along with China and the US (Zhang et al., 2022), producing 1 billion tons of CDW that amounts to 1/3 of the total waste generation in the EU-27 annually (Bonoli et al., 2021). In the region, 85% of CDW is classified as a stony waste (Zhang et al., 2022), in which EOL concrete is the dominant stream.

The diverse environmental, economic, and social impacts of waste generation created the need to manage waste efficiently (Bonoli et al., 2021). In that respect, the EU has been strategizing via Directives over the years to endorse waste management principles across the EU Member States (MS). One of the landmarks towards that purpose was Waste Framework Directive 2008/98/EC, in which the waste hierarchy was established to prioritize prevention, preparation for reuse, recycling, recovery while the least preferred option is disposal (Zhang et al., 2022). At the same time, it set forth the goal of reaching a minimum of 70% of the CDW material recovery rate of the non-hazardous CDW fractions for reuse, recycling, or recovery that includes backfilling, by 2020.

This target directive was legislated in most member states (Hao et al., 2020), while some countries even introduced higher recovery rates, with the Netherlands aiming for 90%. Overall, the level of CDW management legislation in Europe differs per country, with different obligations ranging from sorting, collection protocols, green public procurement, and selective demolition.

Even though direct statistics on CDW generation are not available, Eurostat data on the recycling and recovery rate of mineral waste can be obtained. Mineral waste includes concrete, bricks, mortar, and mixed waste and is the prevailing stream from the demolition

(Cha et al., 2017). According to Zhang et al. (2020), data on mineral waste can be used to estimate CDW generation in Europe since it comprises more than 80% of CDW by weight. In that respect, the EU-28 MS was responsible for generating approximately 372 MT of CDW in the 2018 (Zhang et al., 2022; Eurostat, 2021). As presented in Figure 2, the recovery rate of CDW fluctuates among European countries, with the Netherlands, Ireland, and Malta achieving 100% while the Czech Republic and Greece are underperforming with a 0 % recovery rate. In addition, landfilling seems to be an outdated concept for Europe, with an average 10% landfill rate for the EU MS.

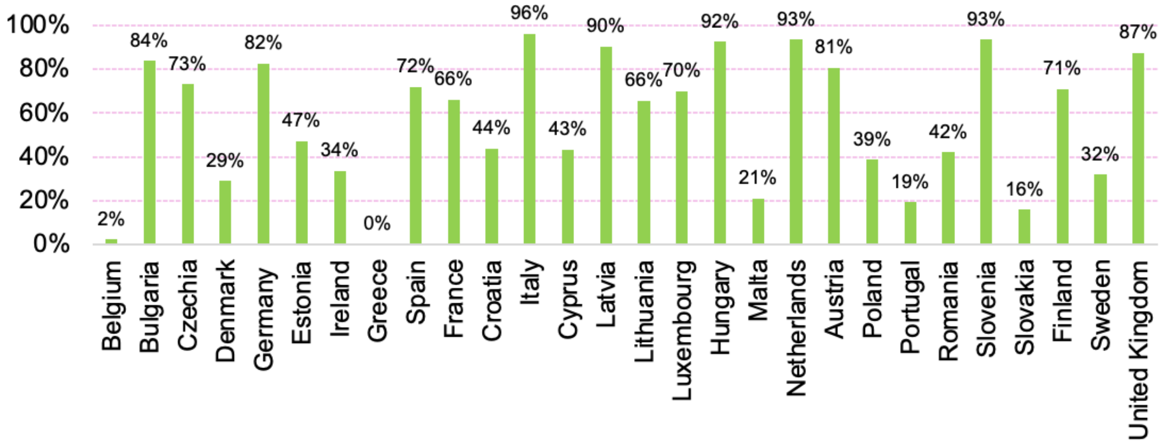


Figure 1. Recycling rate of mineral waste from construction and demolition in 2018 for the EU-28

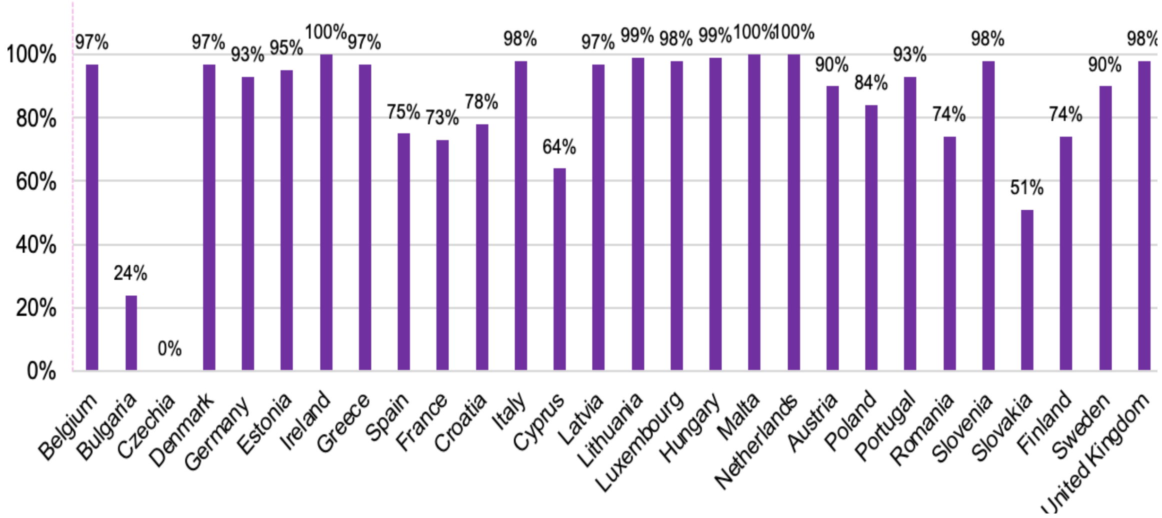


Figure 2. Recovery rate of construction and demolition waste in the EU-28

However, despite contributing to eradicating landfilling practices in Europe, the waste hierarchy provides a broad framework that leaves space for optimization of CDW management practices to increase the added value. For the case of EOL concrete, backfilling or downcycling is defined as “reclamation in excavated areas or for engineering purposes in landscaping” (EC, 2011), following the WFD requirements. Therefore, it is currently the primary outlet for managing EOL concrete (Zhang et al., 2022) while conforming to regulations without reaching the full potential of high-value-added recycling.

1.4 The concept of urban mining & its potential in Europe

With concrete being used in such vast amounts over the centuries, it has accumulated on Earth, marking the Anthropocene period with 900 Gt after the industrial revolution (Habert et al., 2020). Therefore, while we are facing several issues related to natural resource depletion resulting from concrete production, as presented in Section 1.2, opportunities lie in viewing our cities as urban mines.

Moreover, urban mining can be described as the recovery and reuse of materials from sources such as buildings and infrastructure post-consumption that have become obsolete (Metabolic, 2021). According to Arora et al. (2017), residential, commercial, and industrial facilities, as well as CDW, are classified as long-term urban mines compared to packaging waste, electronics, and other commodity materials that comprise short-term mines.

By viewing cities as mines or sources of anthropogenic materials that can be reused and recycled (Arora et al., 2017; Brunner, 2011), the differentiation between waste and resources will no longer apply, and thus raw materials will be extracted from waste (Arora et al., 2017). In that respect, future buildings must be designed for dismantling, recycling, and deconstruction (Zhang et al., 2022) to facilitate urban mining.

However, up to 90% of the existing buildings in countries in the northern hemisphere will still exist in 2050, while approximately 40% of buildings were built before 1960 (Pomponi & Moncaster, 2017). In Europe, most residential buildings were constructed before 1970 (European Commission, 2022), as seen in Figure 3.

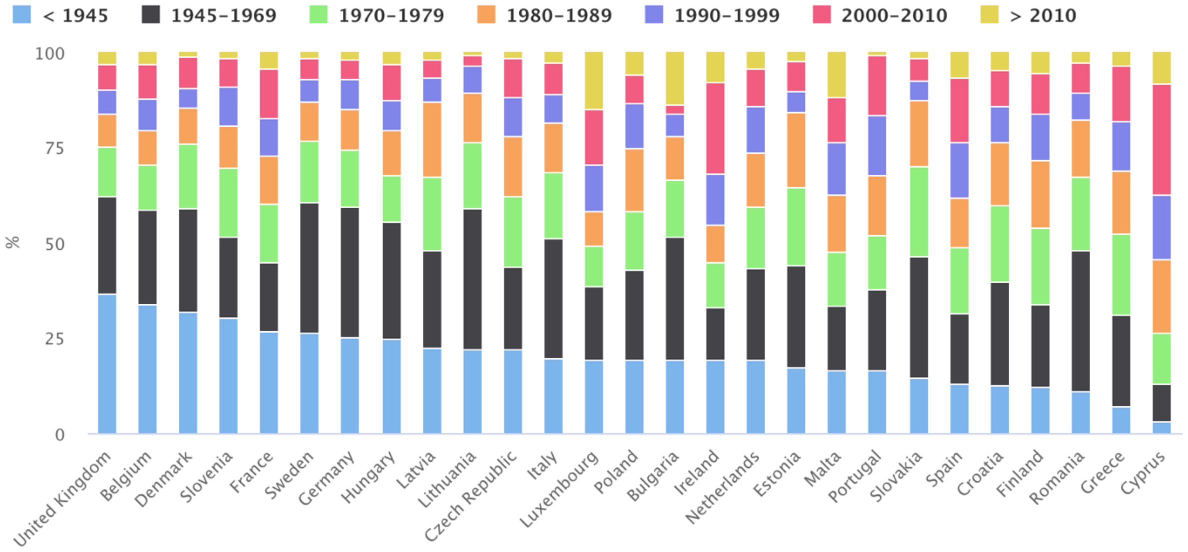


Figure 3. Residential buildings by construction year (European Commission, 2022)

Considering the extended lifetime of buildings that depends on physical, social, and economic parameters but ranges between 60-90 years (Pomponi & Moncaster, 2017), the potential of materials available from the existing stock is substantial. In that respect, focusing on the present and prioritizing the maximization of material supply from existing buildings reaching their end-of-life stage is highly important.

1.5 Circular economy in the construction sector

The urban mining concept follows circular economy practices, which the European Union is endorsing. To optimize the CDW management and steer towards sustainable pathways, the EU aims to eradicate the linear economic model “take-make-dispose” (Benachio et al., 2020) that is predominant in the construction sector. Founded on the principles of unlimited natural resources, it can no longer accommodate the high demand for natural resources.

For this purpose, the European Union has set forth goals for the construction sector within its New Green Deal to facilitate the green transition and carbon neutrality by 2050. In that respect, the Circular Economy Action plan was endorsed in 2020 to support the CDW minimization by prevention, reuse, and improve the recycling of CDW for the production of high-quality secondary raw materials, which can be used to substitute the virgin raw material inputs for new construction partially.

In this context, for the construction sector and considering the building’s life cycle, Benachio et al. (2020) propose the definition of CE as “the use of practices, in all stages of the life cycle of a building, to keep the materials as long as possible in a closed-loop, to reduce the use of new natural resources in a construction project.” CE is based on the 3R strategy of “Reduce, Reuse and Recycle” and aims to revolutionize the CDW management with a cradle-to-cradle approach, ranging from production, consumption, distribution, and recovery of materials (Ghisellini et al., 2018).

1.5.1 3R strategy, challenges, and opportunities

1.5.1.1 Reduction

The reduction of concrete waste, which entails reducing the quantity, negative impacts, and the content of harmful substances (Zhang et al., 2022) is the starting point. According to Zhang et al. (2022), this can be achieved in different phases of the building’s lifecycle, starting from design, the use phase with durable components and materials to the EOL phase with the smart dismantling and selective demolition.

1.5.1.2 Reuse

Regarding reusing building elements, especially concrete structural components, the requirements are rigid since beams and slabs are designed for specific loads depending on their intended use. However, the opportunity to reuse other products and components such as metals, wood, glass, plastic, and insulation components can be seized by the combination of smart dismantling before selective demolition.

1.5.1.3 Recycling

Following the reduction and reuse, recycling concrete is the next step toward achieving circularity in the building sector. Moreover, by definition, recycling is a “recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original purpose or for any other purpose, including the reprocessing of organic waste and excluding energy recovery and the reprocessing into materials that are to be used as a fuel or as a filling material." (Deloitte, 2015). However, high-grade recycling can be defined as reprocessing waste concrete into materials to produce new concrete. The parameters that can potentially hamper the recycling process are diverse and include the cost-effectiveness of the recycling systems, EOL condition of materials and quality of waste, and the secondary materials market condition (Zhang et al., 2022).

Several recycling methods exist, ranging from simple crushing and wet processing to a combination of innovative industrial-scale technologies. Moreover, the Production of Cement and Clean Aggregates from Construction and Demolition Waste (C2CA) is among them, and it entails the combination of Advanced Dry Recovery (ADR) and Heated Air and Classification System (HAS). ADR separates clean coarse aggregates, and HAS produces clean fine aggregates after sorting out the ultrafine fractions, with sizes under 0.25 mm. The ultrafine fractions can replace cement as they present high content of hydrated cement paste (Gebremariam et al., 2020a).

1.5.2 The importance of the EOL phase in the 3R strategy

The common denominator in every part of the 3R strategy in association with the existing building stock is the importance of activities taking place in the EOL stage of the building. In addition, according to Ghisellini et al. (2018), there is a lack of studies accounting for CDW management in the entire chain and the EOL phase. The latter includes pre-demolition audits, smart dismantling, and selective demolition followed by waste treatment, which varies between reuse, recycling or landfilling materials (Ghisellini et al., 2018).

1.5.2.1 Pre-demolition audit

Buildings are distinctive establishments often carried out as individual projects (Gebremariam et al., 2020), and undocumented adjustments or maintenance changes are performed over their extended lifetime. Consequently, data gaps and lack of information before demolition results in the dependence of demolition projects on on-site operations and pre-demolition audits (Hu et al., 2022).

Traditionally, the company contracted to carry out the demolition performs an inspection of the building to compile an inventory of hazardous and non-hazardous materials, the pre-demolition audit. The purpose of that process is to identify the nature, quantity, and level of contamination of the materials extracted during the demolition process. In that respect, the main objective of the pre-demolition audit is to assess the safety risks to the surroundings and the occupational risk (Vermeulen, 2016). However, when the audit's purpose is to identify hazardous substances, the reuse rate for the components of the building is not increased (Deloitte, 2017). In that respect, the European Commission CDW protocol suggests a different approach to the pre-demolition audit, where a qualified expert firstly specifies the quality, quantity, and location of the materials. Consequently, a form of classification for materials is executed depending on their potential for reuse, recycling, or disposal. Finally, the expert should review nearby facilities and markets that accept CDW waste and other identified demolition materials for reuse and recycling (EC, 2016).

Efforts to improve the level of information and efficiency of the demolition process include an image-to-BIM technique, which entails a combination of a handheld camera and unmanned aerial vehicles technologies to extrapolate geometric data and extract the BIM model. The latter offers the opportunity to plan the demolition and waste management options to optimize the timeline of activities, assess safety, and estimate materials and costs(Hu et al., 2022).

1.5.2.2 Demolition

As described in the previous section, an important parameter affecting the outcome of the recycling process is the condition or level of contamination for EOL concrete. Moreover, the state of the EOL concrete is highly dependent on the demolition process. For example, an easy separation process of CDW into homogeneous fractions as much as possible can favor recyclability, increase material valorization (Ghisellini et al., 2018), and result in higher quality secondary materials (Ghisellini et al., 2018, Nunes et al., 2009). The materials derived from the EOL buildings are considered secondary raw materials because they can be recycled and used as raw materials in different applications (e.g., concrete production).

This process is of high importance, as the recovery rates of materials depend on the type of demolition (e.g., conventional, selective, or mixed). At the same time, the quality of secondary materials and products derived from EOL buildings are affected by demolition techniques (Bianchi, 2008). This information showcases the necessity of looking deeper into the role of demolition and the process of acquiring materials on-site.

Traditional demolition begins with the limited initial planning of activities. According to Michael (2018), heavy machinery, exploding and imploding, are employed during the demolition process resulting in mixed waste generation and most materials being destroyed. Consequently, reuse and recycling activities take place, but without prior planning, most of the materials end up in landfills, and the value of secondary materials is lost (Michael, 2018; Liu et al., 2005).

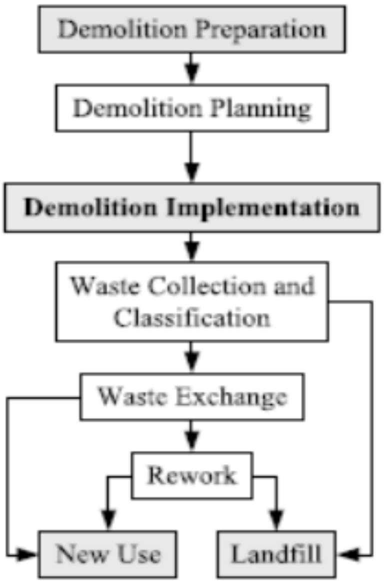


Figure 4. Conventional demolition (Liu et al., 2005)

On the other hand, selective demolition or deconstruction includes separating and sorting building components before recycling. Even though some European countries have established selective demolition practices, it is, in fact, not widely applied in Europe. Nevertheless, selective demolition entails challenges, including that existing buildings have not been designed for dismantling (Pantini & Rigamonti, 2020), and no information on material composition is available before demolition. Therefore, if feasible, separating different components is technically demanding (e.g., separating concrete from bricks or mortar, Pantini

& Rigamonti, 2020). Consequently, selective demolition has increased time, space, and skilled labour requirements.

1.5.2.3 Quality of aggregates

One of the significant side effects of recycled material is the quality of the products that can be disputed due to mixing or pollution, and the perception market actors have on that even though high-quality recycling options exist (Mulders, 2013). Cultural aspects also reveal issues regarding the acceptability of recycled products (Adams et al., 2017). To acquire the market's acceptance and establish a steady demand for secondary materials, quality standards, certification, and labeling should be provided by governmental bodies. This would create a competitive alternative to raw materials that are currently cheaper (Mulders, 2013).

To establish market confidence and acceptance toward high-value secondary materials, innovative quality assurance technologies such as LIBS (Laser-Induced Breakdown Spectroscopy), a technology currently developed by TU Delft are employed to assess and verify the quality of aggregates before their utilization in the production of concrete.

1.6 ICEBERG Circular Case study for concrete recycling

The potential of the above-mentioned technological advancements and best practices at the EOL stage of the building, commencing from pre-demolition audits to demolition and recycling of materials, has been identified for sustainable development in the construction sector (Zhang et al., 2019), and the uptake of a circular economy.

For this purpose, multiple projects have been developed under EU funding in recent years. One of them is ICEBERG, a project that aims to showcase the potential benefits of the innovative recycling systems and technologies that will utilize CDW to produce high-value recovered materials. This will be facilitated by six circular case studies in different countries, including the Netherlands, where the case study on circular concrete will take place. A combination of BIM-supported pre-demolition audits, selective demolition, and high-grade secondary recycling will be performed in the latter.

Moreover, the ICEBERG project’s circular case study on concrete entails two phases. The first phase is deconstructing a 1500 m2 building in the Netherlands by implementing a BIM-supported pre-demolition audit and selective demolition. From the existing building, concrete fractions are collected and separated. After separation, the concrete waste enters treatment to produce different products: coarse aggregates, sieve sand, and dry cementitious material. The second phase entails the use of recycled aggregates to create new concrete in structural ready-mix concrete, prefabricated building blocks, and granular silica aerogel used for thermal insulation. These products will then be employed for constructing a new 200 m2 building.

During the first phase, the ICEBERG project advances current practices by employing a combination of the existing and newly developed information and processing technologies, namely BIM-supported pre-demolition audit, ADR-HAS aggregate processing, and LIBS-facilitated quality control to offer a systemic solution for future concrete recycling. Following pre-demolition audit, the EOL concrete will be retrieved during a highly detailed selective demolition process and then crushed on site. From that process, the reinforcing steel will be removed. The concrete fractions with sizes 0-16 mm will enter the ADR classification system and be sorted to clean coarse aggregates (Gebremariam et al., 2020). The aggregates between 0-4mm exiting ADR will be allocated to HAS. At this stage, the sequence of heating and cooling is used to classify particles based on their size to produce fine aggregates and ultrafine cement components (Gebremariam et al., 2020). Then, LIBS will assess the quality of coarse aggregates exiting ADR with sizes 4-16 mm and the fine products ranging between 0.25-4mm. In the second phase, the aggregates from the recycling process are then supplied to respective facilities for the production of circular concrete and concrete products. Finally, the produced elements will be used in the new circular construction.

Overall, the practices and technologies within the ICEBERG project reflect the state-of-the-art developments in demolition and concrete recycling in Europe. Therefore, in this thesis research, the ICEBERG circular case study is selected as a reference point for innovative concrete recycling in Europe.

1.7 Problem statement and research questions

To sum up, the continuous demand for concrete as a prominent construction material, in combination with the resource depletion and waste management issues associated with its extensive use, presents social, economic, and environmental challenges for Europe. Moreover, even though all EU-28 members have integrated the waste management practices per the WFD in their national legislation, the degree of implementation, in reality, is highly diverse (Deloitte, 2017), which may hinder concrete recycling at a large scale. Meanwhile, the ongoing ICEBERG project demonstrates a set of solutions that include BIM-supported pre-demolition audits, selective demolition, high-grade concrete recycling, and quality assurance. These solutions present a unique opportunity to showcase the potential environmental and economic benefits expected from improved concrete recycling, thus motivating its adoption on a large scale across Europe.

In that respect, this project aims to identify the different performance levels for demolition and recycling in Europe and determine the improvement points for each level in future concrete recycling. The objective can be achieved by answering the following research questions:

- How can the current practices for EOL concrete recycling across Europe be classified? How can the current practices for building demolition across Europe be classified? And how do different demolition practices affect the options for EOL concrete recycling?

- How do the different demolition and recycling practices among the EU MS compare in terms of environmental & financial performance? What are the potential environmental and financial benefits of adopting the combination of BIM-aided pre-demolition audit, selective demolition, and ICEBERG recycling and quality control processes (ADR, HAS, LIBS) for concrete management on a European level?

- What are the hotspots for improvement in each level of the EU demolition and recycling practices? What challenges has the EU to face to improve her future concrete recycling?

1.8 Relevance to Industrial Ecology

The thesis study is relevant to the research field of Industrial Ecology as it touches upon the sustainability problem of managing the voluminous CDW flow in Europe, which demands a systemic perspective in the analysis. The integrated LCA and LCC framework will be used to include all relevant factors through the life cycle of concrete recycling to offer a comprehensive understanding of the associated impacts from an environmental and economic point of view. This research is also societally relevant, as the quantitative assessment of the advanced technologies developed within the ICEBERG project can pinpoint necessary improvements before the large-scale implementation of the proposed circular solutions. The analysis results will facilitate the implementation of changes based on the identified hotspots, both environmentally and financially, along the life cycle stages of the buildings and products.

1.9 Overview of chapters

The next chapter will introduce the methodology, which includes the literature review and the integrated LCA and LCC framework of relevant literature that touches upon the demolition and recycling practices under examination and the integrated LCA and LCC framework. Chapter 3 describes the scenario development process to portray the different performance levels in Europe. In Chapter 4, the integrated LCA and LCC analysis is performed according to ISO 14040:2006, 14044:2006, and EN 15804. Based on the analysis results, the derived conclusions will be presented in Chapter 5. Finally, recommendations for further improvements to achieve circularity in the construction sector based on the conducted research will conclude this project.

2. Methodology

The method used in the research is an integrated life cycle environmental and cost analysis. The LCA and LCC methodologies are well-established internationally (Santos et al., 2019). They have been used widely for the built environment to identify the environmental impacts and economic cost of products and services throughout their lifecycle. A table listing the method, material or waste type under examination, goal, functional unit, impact assessment method, and categories of relevant research projects on LCA and LCC studies of concrete recycling can be found in Appendix A.

2.1 Life cycle assessment (LCA)

In this study, LCA will be used to evaluate the environmental performance across scenarios, because it can identify upstream and downstream trade-offs of technologies, the environment, human health, and resources (Ghisellini et al., 2018) while avoiding problem shifting, e.g., not solving environmental problems but simply allocating them to a different part of the product's life cycle (Guinée, 2002). The LCA method has been selected by (Xicotencatl, 2017; Pennigton et al., 2004) to compare the environmental interventions of recycled concrete across scenarios and identify hotspots or points of attention related to waste, emissions, and resource consumption, which is part of the project's objectives reflected in the research questions. In addition, Ghisselini et al., (2018) and Zucaro et al., (2016) have used LCA to identify the benefits, trade-offs, and opportunities for the improvement of the entire life cycle of the EOL concrete, from the demolition of the building to recycling and the production of new concrete, were identified.

Blengini and Gambarino (2010) combined a Geographical Information System (GIS) and LCA model to study the role of recycled aggregates in the sustainable supply mix, in which the recycled aggregates can substitute natural aggregates and save non-renewable resources. For this purpose, the authors underlined the importance of considering the collection and recycling of CDW as part of a series of processes such as quarrying and transportation. Moreover, it was concluded that the energy consumption and the environmental impacts associated with the recycling process might surpass the savings from primary production and thus deem recycling economically and environmentally unsustainable. Guignot (2015) assessed two schemes for recycling concrete rubble, namely the primary crushing and electrical fragmentation in France, by comparing their environmental impacts with a comparative LCA.

In addition, Ghisellini et al. (2018) reviewed the literature to assess how the CE perspective applies to CDW management and concluded that there is a lack of research on CDW management throughout the construction phases, ranging from designing, procurement, and the demolition stage. Adding to that, the implementation of CE and thus recycling in micro (building material), meso (building), and macro (urban) levels are suggested (Ghisellini et al., 2018; Geng and Doberstein, 2008). Based on the conclusions from Gebremariam et al. (2020) and Ghisselini et al. (2018), further research is necessary regarding the selective demolition at the EOL stage of the buildings and its effects on the quality of the recycled aggregates.

Ghisellini et al. (2018) underline that many researchers use LCA to assess the environmental impacts of recycling without combining other methods to evaluate the associated economic or social dimensions, resulting in a less complete assessment of the sustainability in the building sector. For this purpose, they suggest further research on CE applications with the integration of LCA and LCC frameworks and a cradle-to-cradle approach assessing all the life cycle phases of buildings.

Additionally, in the papers reviewed by Röck et al. (2021), no EOL scenarios are included in the LCA, and sensitivity and environmental hotspot analysis are limited. Most studies do not account for material-related impacts on building stock (Röck, 2021). For example, single research is mentioned to perform a sensitivity analysis to assess the effects of substituting virgin materials with recycled aggregates. Finally, Röck et al. (2021) identify a research gap in associating the evaluation of building life cycle performance with the targets set by the EU. This can be addressed by assessing construction products based on a revised Construction Product Regulation with recycled content standards (European Commission, 2020), corresponding material recovery targets compared to goals set by EU legislation, etc.

2.2 Life cycle costing (LCC)

Sustainability in construction is based not only on environmental but also on economic and social pillars (Santos et al., 2019). Therefore, parallel to LCA, it is essential to assess the costs of each life cycle stage (e.g., demolition, manufacturing, etc.) and the cost-effectiveness of every product and process. This assessment ensures a comprehensive approach that considers the economic performance of the technology, which is currently identified as a knowledge gap. For this purpose, standard cost-accounting systems are inadequate since demolition and recycling are not included in the traditional accounting system (Gluch and Baumann, 2004). In that respect, LCC is a method that can enable the cost assessment of initial and future operational costs (Gluch and Baumann, 2004) to facilitate the comparison across scenarios. Acknowledging the costs associated with transport, machinery, utilities, labour, and materials purchase, Xicotencatl (2017) examined scenarios for recycling concrete rubble in the Netherlands by combining LCA and LCC. The results of this study showcase improved environmental performance for recycling concrete rubble into coarse aggregates with ADR, at a higher cost compared to regular crushing in the Netherlands.

Similarly, Giorgi (2019) studied the LCA and LCC methodologies for circularity in buildings that showcase the lack of data for the buildings' construction and EOL phase. Gebremariam et al. (2020) researched innovative industrial-scale technologies (e.g., ADR and HAS or C2CA) and issues concerning the quality of recycled aggregates, concluding that the latter depends on the EOL handling and processing of concrete waste.

To sum up, the review of existing LCA and LCC studies on concrete recycling shows a lack of research on selective demolition, including practices carried out in the EOL stage of the building (e.g., pre-demolition audits) and how these affect the quantity and quality of recycled aggregates. In addition, a combination of research methods in integrated forms and a cradle-to-cradle scope for concrete products are offered for further research, along with different scenarios, sensitivity, and hotspot analysis for EOL scenarios.

This study will fill the knowledge gap by examining the role of pre-demolition audit, selective demolition, and different options for recycling EOL concrete from a demolished building to produce raw materials for concrete production. This will be carried out with the combination of the LCA and LCC methodologies through an existing integrated framework, presented in the next section.

In detail, this project assessed the total environmental impacts and costs associated with the demolition, sorting, manufacturing, use, and end-of-life and the respective stakeholders. Furthermore, the role of pre-demolition audit and selective demolition in different levels of detail within the developed scenarios is investigated to shed light on the EOL stages of the buildings that are rarely explored in the existing literature.

2.3 Integrated LCA and LCC framework

Frameworks that combine LCA and LCC have been proposed and applied in several studies. (Zhang et al., 2019) proposed an integrated LCA and LCC framework (Figure 5), which comprises four steps that include a joint goal and scope definition, an environmental and economic inventory, an impact assessment step as well as interpretation.

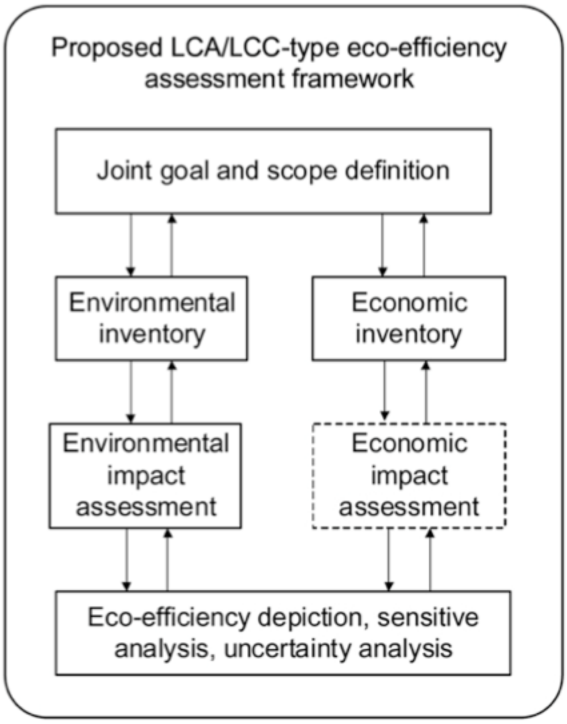


Figure 5. Overview of the integrated LCA & LCC framework, (Zhang et al., 2019)

This research will follow the framework given in Figure 5 to assess the environmental and economic aspects of the product systems from a life cycle perspective. The LCA and LCC studies will be executed in parallel under the ISO 14040 and the EN 15804 standards, respectively, sharing the same structure, system boundary, and functional unit. The interpretation stage entails the sensitivity analysis, consistency and completeness checks, conclusions, and recommendations and it is carried out together for the LCA and LCC. The eco-efficiency depiction and uncertainty analysis were not part of this study.

The present LCA and LCC case study will be carried out in two steps. The first step (Chapter 3) develops the scenarios, which represent various levels of the demolition and concrete recycling practices in Europe. And the second step (Chapter 4) quantifies the performance difference between the scenarios using an integrated LCA and LCC framework.

The LCA research, including the data analysis and LCA modelling, was performed in Activity Browser (AB), an open-source software developed by the Institute of Environmental Sciences of Leiden University (CML). AB entails features such a graphical user interface that facilitate the modelling, analysis, and comparison of different scenarios along with contribution and sensitivity analysis of the LCA results. The LCC research was carried out with Excel.

3. Scenario development

3.1 CDW management practices in Europe

3.1.1 Literature review approach

It was imperative to understand the current status of circularity practices around Europe to quantify the potential of innovative technologies and solutions for demolition and recycling. Starting from the demolition of a building, an overview of current practices that shape the quantity and quality of the generated waste can reveal how these consequently affect the waste management options (reuse, recycling, etc.) that follow. This understanding can facilitate the classification of current practices for building demolition and EOL concrete recycling in Europe with qualitative data, set the base for their quantitative analysis, and thus provide answers to the first research question of this project.

On a first level, the review of CDW management policies and the identification of legislative or non-legislative additional practices that contribute to circularity, such as pre-demolition audits, landfill taxes, etc., is essential. However, on the second level of analysis, considering the individuality of each deconstruction project with every building being a unique entity, the actuality of practices "on the ground" might differ from what is encouraged by policies. In that respect, the European Union has commissioned several research projects that include case studies such as the "Resource Efficient Use of Mixed Wastes" carried out by Deloitte (2017). In addition, individual reports for each member of the EU-28 were published in 2015, with information on the legal framework of each country, non-legislative measures, CDW management in practice, and national statistics data.

These documents are part of the literature review and were utilized to portray circularity practices for EOL concrete management in the EU-27 in a realistic way. At the same time, a focus on pre-demolition audits and selective demolition, their definition, and the specifics of if and how they are performed were points of attention. Consequently, methods for concrete recycling were reviewed to specify common practices among the EU-27.

The primary objective of the literature review is to map out CDW management practices and explore the performance levels across the EU-27. The European Commission has laid out the groundwork in Deloitte's "Resource Efficient Use of Mixed Wastes" report (2017). A part of the results was the development of a scoring system reflecting different levels of maturity, ranging from initial, developing, implemented, and improving or optimizing for a set of CDW practice categories, including landfill management and diversion, waste management infrastructure, prevention, data, fiscal measure, etc. The results portrayed the diversity in performance levels and adopted European practices that were translated in scenarios I and II, reflecting the BAU and BP performance, respectively.

A closer look at on-site operations facilitated the identification of sustainable CDW management practices, among them pre-demolition audits. At the same time, selective demolition is recognized as a promising measure. In addition, both the pre-demolition audit and selective demolition are included in the waste identification, source separation, and collection section of the checklist within the Construction and Demolition Waste Protocol (EC, 2016). However, these activities are not strictly defined; thus, their application varies in different countries.

3.1.2 Pre-demolition audits

According to Deloitte (2017), there is no uniformity in applying pre-demolition audits in the EU even though its potential to increase recycling, if performed in detail, is known. Currently, pre-demolition audits are introduced in the legislation of 17 European countries, including Belgium and Luxemburg, Finland, and others, as showcased in Figure 12, which visualizes data from “Resource Efficient Use of Mixed Wastes.”

As described in section 1.5.2.1, the motivation before auditing the building scheduled for demolition is to identify asbestos and hazardous substances that can be considered the business-as-usual (BAU) practice in Europe. Furthermore, according to García et al. (2017), waste audits are usually either not available or detailed, while in some cases, they can be deemed unreliable. Typically, the pre-audits are executed by the demolition company to estimate the costs of demolition activities for private use (García et al., 2017). Consequently, the BAU practices in Europe entail a basic form of a pre-demolition audit to identify hazardous materials and estimate costs.

In some other countries, such as Austria, an improved approach to identifying reusable components and hazardous materials is required (Cárcel Carrasco & Peñalvo López, 2020), while a small portion of MS proceeds to classify additional material streams. In this context, steel is usually identified, separated (Ruggeri et al., 2019), and diverted to recycling due to high revenues. For example, documentation of identified materials in the Netherlands is necessary to showcase conformity with regulations. This type of pre-audit reflects the average best practice among the EU-27 members. In addition, Belgium has enforced the obligation to plan waste management in advance and prepare material inventories before demolition (Deloitte, 2015a).

Figure 6. Illustration of pre-demolition audit practices within the legal framework of the EU-27

The previously described versions of pre-demolition audits are dependent on two-dimensional drawings, which, in some instances, are unavailable, especially for older buildings. However, this approach will eventually become redundant with the broader use of BIM. Currently, for new buildings, BIM supports three-dimensional drawings with additional geometrical and semantical information on materials, while it also includes construction specifications and details from the manufacturer (García et al., 2017). According to Carcía et al. (2017), the use of BIM models as sources of information before demolition works has been identified as promising due to its financial benefits associated with better visualization, easily accessible information, and an embedded material inventory that can increase process productivity.

Because BIM models are not available for the demolition of existing buildings, TECNALIA has developed the BIM4DW, a portable editor that supports assembling a waste inventory on-site. Its purpose is to facilitate the maximum recovery of materials in existing buildings scheduled for demolition to optimize the demolition processes, planning, and managing waste. This objective can be supported by collecting and managing the information about the building components and available materials.

This innovative approach to pre-demolition audit is newly developed and thus not implemented on a large scale. Nevertheless, it reflects the highest level of performance for pre-demolition audits currently available in Europe and is part of the ICEBERG case study. Therefore, it was integrated into the development of scenario III or EU FP for the analysis, that will be introduced in the next sections. Further details on the BIM4DW tool and how it was used in the demolition of the Eikenstein detention center can be found in Section 4.4.3.

3.1.3 Selective demolition

To scope out the practices concerning demolition in Europe, the respective reports on “Construction and Demolition Waste Management” in every EU-27 MS, as part of the “Resource Efficient Use of Mixed Wastes” initiative commissioned by the European Commission, were reviewed. The different practices and their application in the EU-27 MS can be found in a summary table in Appendix A.

As previously described for the pre-demolition audits, selective demolition is classified as an obligation in few EU-27 MS, as presented in Figure 7, to steer away from currently prevailing non-selective demolition practices. However, the objective remains to separate hazardous substances and, in limited cases, other materials. Usually, on-site separation is not part of the selective demolition process despite its known contribution toward on-site reuse, the distinction of individual treatment options for each material, and the overall improvement of the recycling process (Deloitte, 2017).

Different tracks and approaches between the EU-27 were identified, starting from national and expanding to regional differences. For example, in Spain, there is no national obligation for selective demolition, although specific separation requirements per waste flow are established regionally in the Basque country (Deloitte, 2015b). Likewise, in Germany, regions have developed respective CDW management plans that recommend selective demolition (Deloitte, 2015c). In Finland, selective demolition is a national obligation, and the objective to plan the demolition with the purpose of recycling components is indicated (Deloitte, 2015d). In

Slovakia, the removal of asbestos before demolition work is encouraged (Deloitte, 2015e). In Luxemburg selective demolition is a national obligation (Deloitte, 2015f), while in Sweden, the identification and management of hazardous waste are required before demolition works (Deloitte, 2015g). In Lithuania, records of CDW, separate collection of inert, recyclable, and municipal waste, non-recyclable and hazardous waste is enforced (Deloitte, 2015h).

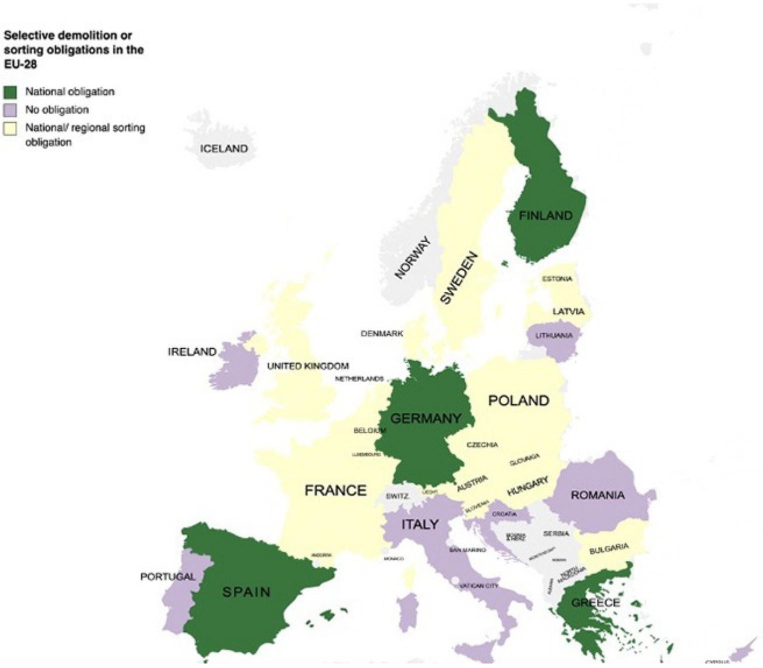


Figure 7. Illustration of selective demolition within the legal framework of the EU-28 MS

Based on the above, a disorderly framework is evident within Europe that arises the matter of definition and intended purpose for both pre-demolition audits and selective demolition. Consequently, from the literature review, three types of demolition practices can be currently identified in Europe. Non-selective demolition, selective demolition to separate hazardous waste, and selective demolition to sort materials and divert them accordingly to reuse and recycle. In that respect, for scenario I, which reflects the BAU practices, non-selective demolition will be considered. Moreover, for scenario II, which represents the best practices, selective demolition to reuse or recycle limited items will be modeled.

Finally, the ICEBERG selective demolition process encompasses the European Commission’s CDW protocol guidelines, where the quantity, quality, location, and classification of materials considering their prospective reuse, recycling, or disposal is registered. This process was carried out in advance, and local market representatives were contacted to retrieve components from the building and plan their utilization in different projects. This will be reflected in scenario III or EU FP.

3.1.4 ICEBERG Circular Concrete Case study

Among the project’s objectives is to evaluate the potential that state-of-the-art solutions, currently not widely implemented or novel and thus unavailable on a large scale, entail for the future of concrete recycling.

As presented in section 1.6, the ICEBERG case study on concrete combines the best available practices consistently from the EOL of the building to the production of new concrete along with the innovative technological solutions of HAS, ADR, and LIBS for concrete recycling. The information outsourced from this project was adapted and used to develop the EU FP, which reflects the future practices for demolition and concrete recycling in the EU.

The project begins from the EOL phase of the Eikenstein detention center, a building in Zeist, Netherlands. It consists of two parts; a monumental section that will be renovated and a former juvenile detention center, which was demolished. GBN, an ICEBERG partner, carried out the planning and supervision of the building demolition. In Table 3, an overview of key information about the project can be found.

Figure 8. The Eikenstein detention center in Zeist, Netherlands.

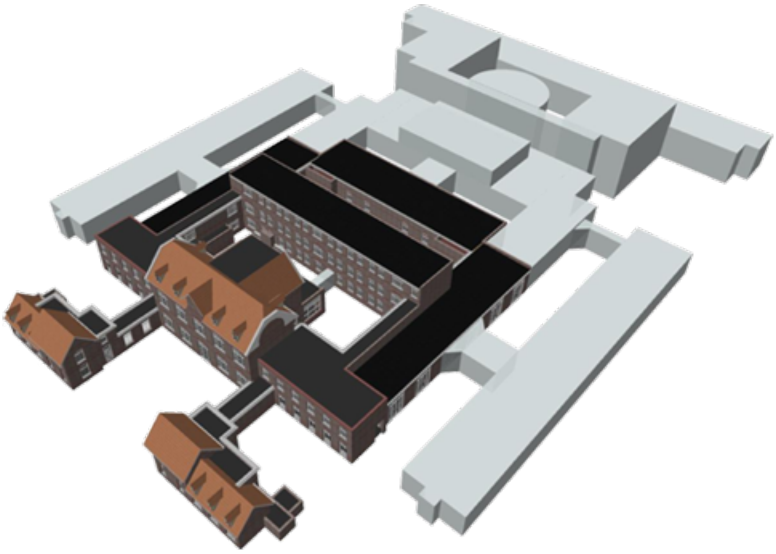


Figure 9. The Grey area is the non-monumental part that will be demolished (provided by Frank Rens and Bente Kamp, GBN)

Table 3. General information about the demolished building (provided by Frank Rens, GBN)

Information on the Eikenstein detention center	
Location:	Utrechtseweg 37, 3704 HB Zeist
Year of construction	Monumental part (not part of scope): 1905 Detention center = 1987 / 2001
Demolition start date:	May-22
Demolition end date (expected):	Aug-22
Reason for demolition:	Change of usage, from detention center to residential buildings
Initial decommissioning	The case-study is a juvenile detention centre. Therefore, components and materials are not easy to remove, which can increase the time required for the demolition.
Type of building:	Non-residential
Main use	Detention center
Type of construction	Concrete
Overall surface (m^2)	10.000
Surface to be demolished (m^2)	6.000
Floors	4
Basement	Yes
Physical condition of parts and elements (decay, insect attacks, mechanical damage)	Good condition, usage damage

Before the demolition project commenced, a BIM-supported pre-demolition audit by TECNALIA, an ICEBERG partner, was performed (Figure 10). The purpose was to identify and quantify the available materials that could potentially be harvested from the building and assess their management option (e.g., reuse, recycle, energy recovery). Considering that the demolished building was previously a detention center, an increased difficulty in dismantling materials and detaching components for reuse and recycling (Figure 12 and 13) was anticipated. A selective demolition (Figure 11) was performed before diverting materials to reuse and recycling in nearby facilities. The EOL concrete was processed with ADR and HAS (C2CA technology) to produce coarse and fine aggregates, which then underwent the quality assurance process by LIBS. The next step was to produce new pre-mix concrete and prefabricated elements by substituting natural with recycled aggregates, which will be used in a new building. However, this project will be limited to the production of aggregates and not consider the production process and new building implementation.

3.1.4.1 Data adaptation

GBN provided the data sourced by the case study in an Excel data template (Appendix B), designed by RINA and adapted for this project. Since the case study building is a former detention center, it has unique characteristics associated with additional costs or man hours, such as an increased difficulty in detaching components. Therefore, it can be argued that it is not an accurate representation of an average building within the existing stock of Europe. In addition, the project client had a specific demand of 1000 tons of concrete waste to be treated into coarse and fine aggregates by the C2CA technology and LIBS. This quantity does not reflect the real potential for the amount of concrete that could be derived and processed, which surpasses the 1000 tons approximately by 6-fold. Since the objective of this research is to assess the utmost potential that the EU's state-of-the-art solutions encompassed in ICEBERG entail, it is assumed that the maximum quantity of concrete fractions could be possibly derived with the combination of pre-demolition audit and selective demolition from the building was recycled. Overall, to acknowledge the above limitations, the primary data were adapted to reflect how the ICEBERG circular solution would be applied if the inherent limitations of the Eikenstein were surpassed. This will be reflected in the EU FP scenario. The EU BAU and EU FP scenarios were supported with estimations by Frank Rens and Bente Kamp from GBN.

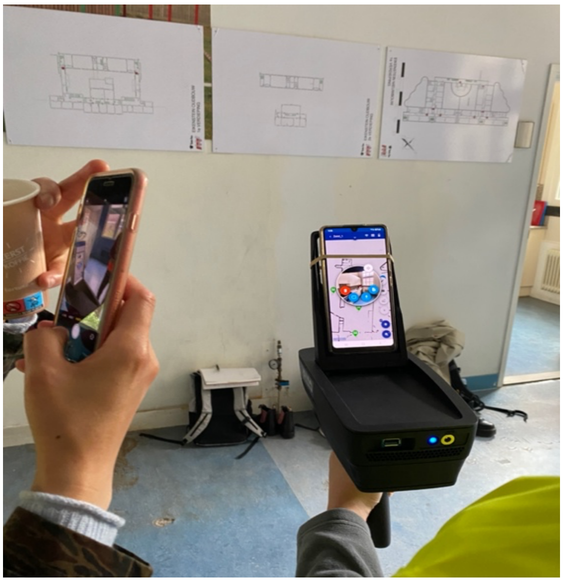


Figure 10. Equipment for pre-demolition audit

Figure 11. A room prepared for selective demolition

Figure 12. Wood collected for recycling

Figure 13. Doors collected to be reused

3.1.5 Overview of formulated scenarios

Based on the above, two scenarios that portray the different performance levels identified during the literature review were developed. These reflect current circularity practices concerning pre-demolition, demolition, and concrete recycling in Europe. Moreover, scenario I, from now on EU BAU, and scenario II, from now on EU BP, were modeled to represent the most common and average best practices, respectively.

Moreover, the EU BAU scenario entails a basic pre-demolition audit to identify hazardous substances as carried out in countries with no legislated pre-demolition audits (e.g., Lithuania, Greece, Latvia etc.), excluding the 17 MS which have done so (e.g., Luxemburg, Finland, Belgium etc.). The demolition in this scenario is considered non-selective and the EOL concrete is crushed into RBA, as widely applied in the majority of European countries.

In the EU BP scenario, as performed in several EU MS, including Austria and the Netherlands, a form of selective demolition aims to identify hazardous substances and a limited quantity of materials for recycling. The demolition is considered selective, with the purpose to reuse and recycle materials, as executed in countries including Germany, Finland, Spain, and the Netherlands. Similarly to the EU BAU, the EOL concrete is crushed into RBA.

The EU FP scenario is based on the ICEBERG case study for concrete in the Netherlands. The demolition project starts with a BIM4DW-supported pre- demolition audit resulting in a detailed material inventory. This ensures an optimized strategy for selective demolition, that aims to maximize the reuse and recycling of components. The EOL concrete is processed using C2CA technology to produce coarse, fine, and ultrafine aggregates. The recycled coarse and fine aggregates are quality controlled by LIBS.

Overall, the three scenarios were developed with a combination of a literature review for the business-as-usual and best practices in Europe and the ICEBERG case study for the circular practices and technological innovation in the EU FP scenario. All in all, the three scenarios are formulated as follows:

Table 4. Overview of practices and technologies in each scenario

Scenarios	**Pre-demolition audit**	**Demolition**	**EOL concrete treatment**
EU BAU	Hazardous substances	Non-selective	Crushing into RBA
EU BP	Hazardous substances and limited identification of materials for reuse and/or recycling	Selective with some materials being reused and/ or recycled	Crushing into RBA
EU FP	BIM4DW supported, full material inventory and optimized strategy for reuse and recycle	Selective, all materials are reused and recycled	High grade recycling into coarse and fine aggregates for new concrete production

4. Integrated LCA and LCC

4.1 Goal and scope definition

4.1.1 Goal

In this project, the integrated LCA-LCC study aims to quantify and compare the environmental and financial characteristics of the ICEBERG circular case study, as portrayed in the EU FP scenario with the European BAU and BP on the recovery and recycling of EOL concrete derived from a building scheduled for demolition. The analysis is carried out from grave to cradle, spanning over the demolition of the Eikenstein building, where EOL concrete is generated to produce aggregates for new concrete.

Furthermore, an additional objective is to support:

- the further development of the ICEBERG technologies, namely ADR, HAS, and LIBS, by identifying points of improvement in terms of environmental and financial impacts

- the uptake of circular economy practices within the construction sector, by identifying points of improvement from an environmental and economic point of view, in the BAU and BP in Europe

4.1.2 Scope

The LCA-LCC analysis was carried out based on the demolition project of the non-monumental part of the Eikenstein building, located in Zeist, Netherlands, that began in May 2022. The demolition is part of the European Union's Horizon 2020 ICEBERG project and was executed by GBN, an ICEBERG project partner.

GBN performed a pre-demolition audit to prepare an inventory with information on materials quality, quantity, and location. At the same time, an additional objective of the pre-audit was the identification of components and appropriate waste management options, as well as locating potential local markets for reuse. Consequently, a selective demolition was performed to maximize the harvested components and materials from the EOL building and divert them to reuse, recycling, or energy recovery. That included retrieving EOL concrete to recycle into coarse aggregates to produce new concrete. The processing of the concrete fractions was performed with the combination of ADR and HAS to produce coarse, fine, and ultrafine aggregates. Consequently, the quality of coarse and fine aggregates was evaluated by LIBS. Three alternative product systems were modeled, assuming that the quality of recycled and natural aggregates used for producing new concrete is equivalent.

Considering that a demolition is a one-time event, the primary data for the analysis are derived from the case study and were adapted based on expert opinion from field experts working on the demolition project, to model the EU FP scenario. The EU BAU scenario represents how the demolition would have been executed with average European practices. In contrast, the EU BP scenario portrays the current best practices adopted by European countries. For these scenarios, adaptations of the primary data based on estimations provided by actors within the construction sector were used.

The profiles of all three scenarios, from environmental and financial standpoints, are described per the EN 15804 standard, as can be seen in Table 5:

Table 5. EN 15804 standard for stages Eikenstein project

Building	Stage	EN15804 module	
Eikenstein detention center	End of life	C1	Dismantling and demolition
		C2	Transport to waste processing and disposal facilities
		C3	Waste processing
		C4	Disposal
	Product	A1	Raw material supply
		A2	Transport of raw materials
		A3	Manufacturing

4.2 Function, functional unit, alternatives, reference flows

From the demolition of the Eikenstein detention center, the mixed waste containing stony rubble and EOL concrete fractions was estimated, as presented in Table 6. In reality, only 1000 tons of concrete were allocated to concrete recycling with ADR, HAS, and LIBS due to specific objectives set by the project commissioner. However, for the purpose of this research, it is assumed that from the total amount of mixed waste from demolition, the maximum amount of concrete fractions for each system, depending on quality limitations related to the demolition activities, were processed.

Table 6. Material inventory originally derived from the Eikenstein demolition

Material	Amount (tons)
Total stony waste from demolition	**10500**
Stony rubble	9500
EOL concrete	1000

The original quantities were adapted based on estimations from actors within the construction sector involved in the demolition project of the Eikenstein building to reflect how the demolition practices in each scenario would affect the composition of the stony waste. In the EU BAU and EU BP, there is no intention to recycle waste into high-quality aggregates; thus, 100% of stony waste is considered rubble and crushed into road base aggregates. Finally, in the EU FP, about 85% of the stony waste is EOL concrete that can be fed into the C2CA technology for high-grade recycling. An overview of the adapted data can be found in Table 7.

Table 7. Material inventory adapted for the purposes of this research

Material	EU BAU (tons)	EU BP (tons)	EU FP (tons)
Total stony waste from demolition	**10500**	**10500**	**10500**
Stony rubble	10500	10500	1500
EOL concrete	0	0	9000

In this project, different systems are under evaluation; thus, it is critical to ensure their comparability (Zhang et al., 2019; ISO, 2006a). The three systems have different outputs; therefore, the product systems were expanded and equalized to all the highest outputs, to facilitate the functional equivalence of the three scenarios. Thus, the basket of functions for the equivalent product systems to compare the EU BAU, EU BP, and EU FP scenarios are as follows:

Table 8. Functional unit for comparative analysis of the product systems

		Functional unit
Reference in flow diagrams	a	Treatment of 10500 tons of mixed stony waste
	b	Producing 6840 tons of coarse aggregates for concrete
	c	Producing 1728 tons of fine aggregates for concrete
	d	Producing 432 tons of cementitious materials for concrete
	e	Producing 10500 tons of RBA

The reference flows for each product system can be found in Table 9.

Table 9. Reference flows for the three scenarios

Eikenstein building	Functional units	Reference flows		
		EU BAU	EU BP	EU FP
Modules C1-4	Demolition of the Eikenstein building	Treatment of 10500 tons of stony waste		
Modules A1-3	Production of 6840 tons of coarse aggregates	6840 tons of NCA		5040 tons of RCA from ADR and 1800 tons of RCA from on-site crushing
	Production of 1728 tons of fine aggregates	1728 tons of NFA		1728 tons of RFA from HAS

	Production of 432 tons of cement (cement, or cement & ultrafine products	432 tons of cement	432 tons of ultrafine products from HAS
	Production of 10500 tons or road base aggregates	10500 tons of RBA from on-site crushing	1500 tons of RBA by on-site crushing and 9000 tons supplied

Furthermore, details on the output of each system, in regard to the production of natural or recycled aggregates, as well as how they were equalized to the highest output is presented in Table 10.

Table 10. Explanatory table for computing the reference flows in the LCA

				Produced		**Supplied**			**Total (tons)**	
1	building	EU BAU	0	RCA		6840	NCA		6840	CA
			0	RFA		1728	NFA		1728	FA
			0	UF		432	Cement		432	Cement
			10500	RBA		0	RBA		10500	RBA
1	building	EU BP	0	RCA		6840	NCA		6840	CA
			0	RFA		1728	NFA		1728	FA
			0	UF		432	Cement		432	Cement
			10500	RBA		0	RBA		10500	RBA
1	building	EU FP	6840	RCA		0	NCA		6840	CA
			1728	RFA		0	NFA		1728	FA
			432	UF		0	Cement		432	Cement
			1500	RBA		9000	RBA		10500	RBA

4.3 Inventory analysis

The product system for each alternative will be defined in this section, including the system boundary, flow diagrams for each alternative, and the necessary cut-offs. In addition, the data quality, and the selected methods to treat multifunctionality and allocation will be addressed.

4.3.1 Economy-environment system boundary

Since the ICEBERG circular case study is carried out in the Netherlands, the country will be the geographical reference for this study. In the system boundary, four stages of the lifecycle are considered: demolition, transportation, concrete waste processing, and raw material supply. In the demolition phase, all known processes and activities are evaluated for each system, and all types of machinery and equipment are assumed to be identical. For off-site recycling, transporting the stony waste and EOL concrete fractions to the recycling plant is considered. For the recycling on-site, the transportation of the necessary equipment on location is accounted for.

The concrete waste management process entails the treatment of EOL concrete into secondary products, such as fine and coarse aggregates, for manufacturing new concrete. As described in section 4.2, the technological systems have different outputs. For example, the C2CA technology produces coarse and fine aggregates, while the on-site crushing produces only coarse aggregate that can be used in concrete manufacturing.

In addition, according to (Zhang et al., 2019), the secondary raw materials, namely the fine aggregates and ultrafine products from HAS, can replace virgin sand and cement, respectively, in producing new concrete. To ensure comparability, the production processes for the supply of raw materials, including coarse and fine aggregates and cement, have been added to the respective product systems. The economic and environmental benefits of the reuse and recycling of other components, excluding EOL concrete fractions, are also considered.

Furthermore, no direct emissions from foreground processes were provided during the data acquisition. Thus, the environmental interventions are retrieved from the Ecoinvent 3.7.1 database or by using proxy background processes.

4.3.2 Cut-offs

Several flows were not included in the product systems due to a lack of data. The wood and plastic contaminants that are part of the stony waste derived from demolition were not measured and thus cannot be quantified within the system. Similarly, the hazardous waste removed during the pre-demolition process, including asbestos and chromium, was not reported. In addition, the environmental flows, or direct emissions such as the noise from the demolition activities, odor or dust, and pollutants from dust control were not measured or estimated on a case-specific level. Therefore, these flows were not included in the analysis.

4.3.3 Flow diagrams, product systems, unit processes

In reality, the demolition yielded two large streams, namely stony rubble, and concrete fractions, with sizes ranging up to 500 mm. The first stream contains contaminants such as wood, plastic, and other materials that were not quantified. For the EU BAU and BP scenarios, it is assumed that the demolition process would only result in a large stream of stony rubble.

The reusable elements harvested from the demolished building were listed in a material inventory along with their appointment to local markets and the collected revenues from their reuse and recycling. For some of the components, apart from communicating with the local market stakeholders after the pre-demolition audit, the demolition company was not involved in harvesting the materials from the Eikenstein building or transferring them to the respective facilities. Therefore, the acquisition of the components for reuse and recycling by the market stakeholders, such as secondhand stores, is considered free of burden. However, the reuse or recycling of the building components is associated with financial benefits from proceeds and reduced burdens from waste processing, including landfilling or incineration, and thus was included in the analysis.

The illustrations of the product systems can be found in Figures 14, 15, and 16 for the EU BAU, EU BP, and the EU FP, respectively. Consequently, the unit processes modeled within each product system will be described.

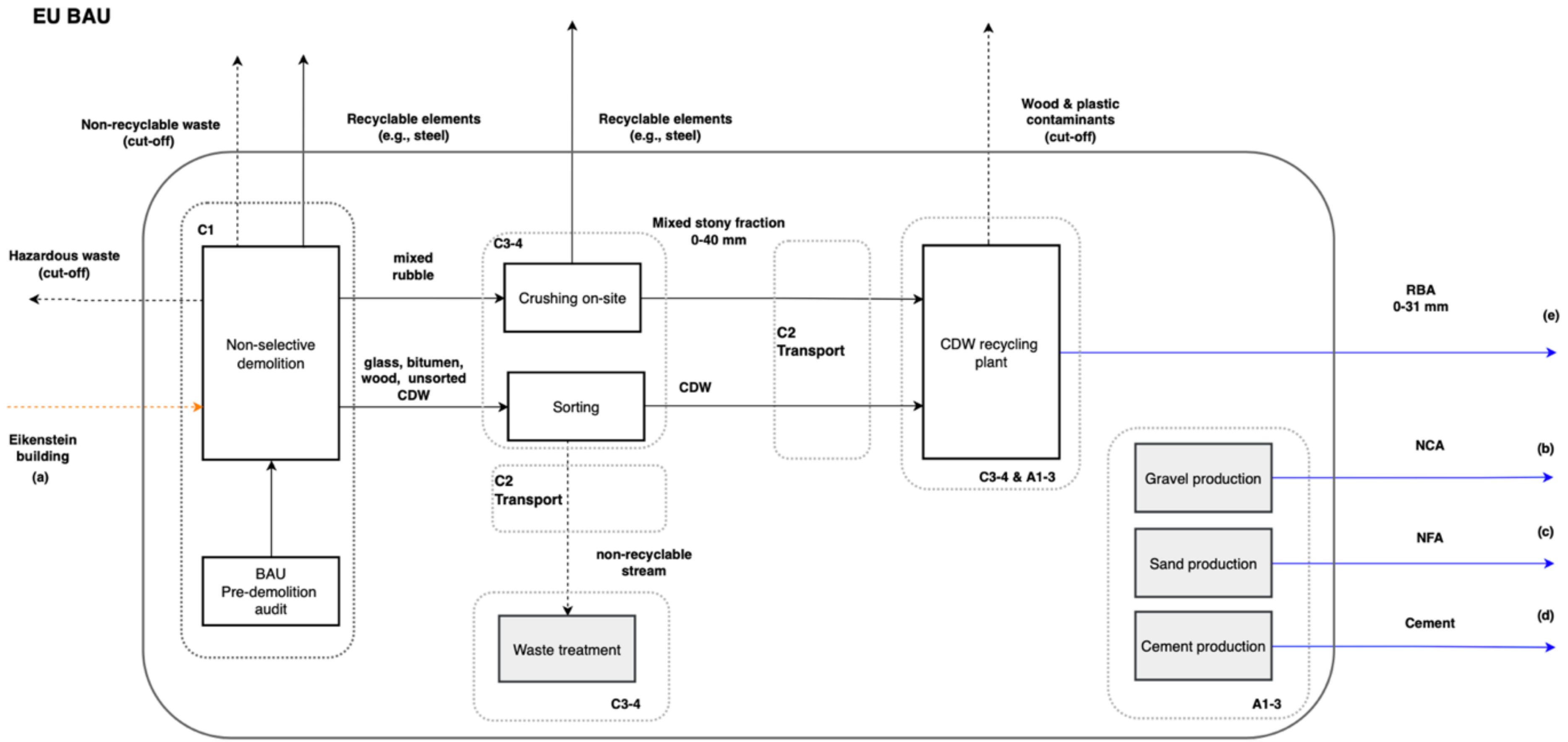


Figure 14.Flow diagram for the product system of the EU BAU scenario

Abbreviations

EOL: End of life
CDW: Construction and Demolition Waste
RBA: Road base aggregates
RCA: Recycled Coarse Aggregates
NFA: Natural Fine Aggregates
NCA: Natural Coarse Aggregates

Legend

⬚ System boundary
⬚ EN15804 information module
☐ Foreground process
▨ Background process
M Multifunctional process

→ Good
⇢ Waste
} Economic Flows

→ Reference flow for aggregate production
→ Reference flow for building level comparison

EU BP

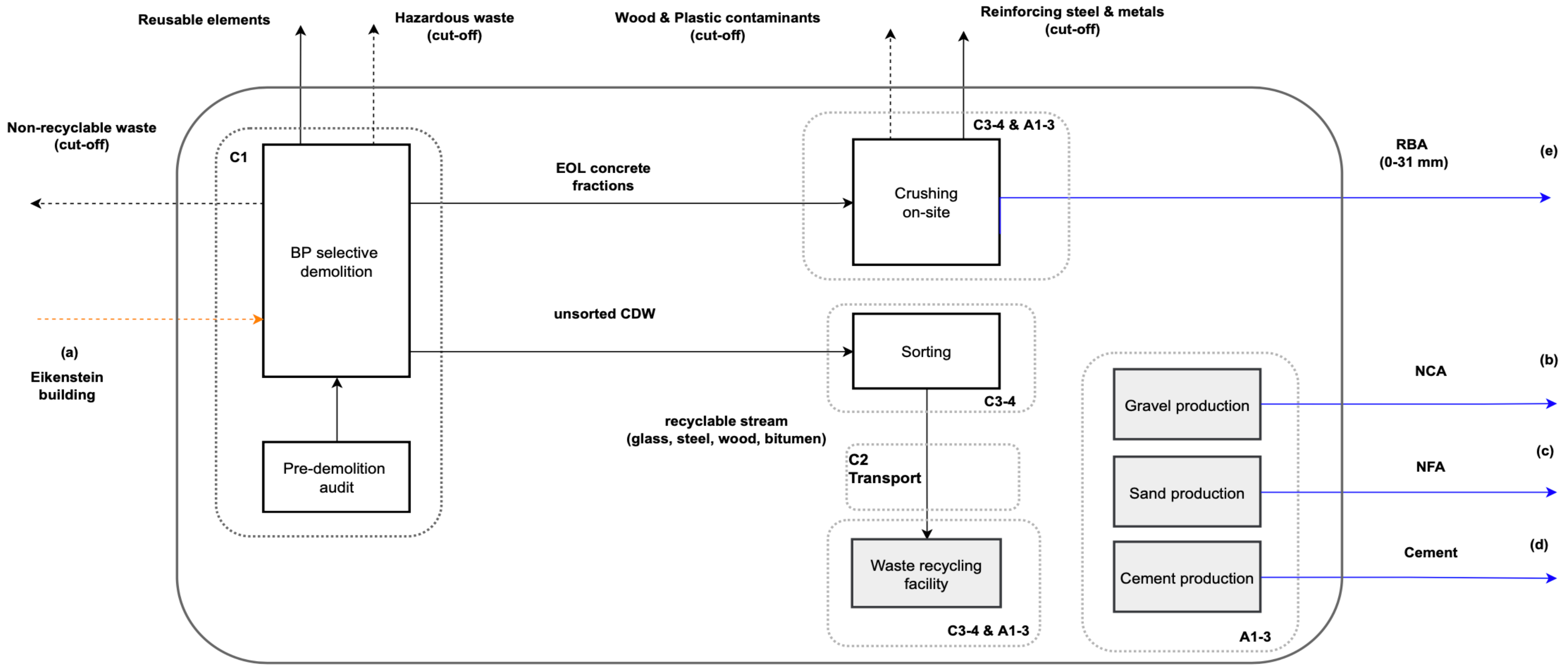


Figure 15. Flow diagram for the product system of the EU Best Practice scenario

Abbreviations

EOL: End of life
CDW: Construction and Demolition Waste
RBA: Road base aggregates
RCA: Recycled Coarse Aggregates
NFA: Natural Fine Aggregates
NCA: Natural Coarse Aggregates

Legend

⬚	System boundary	→ Good	Economic Flows
⬚	EN15804 information module	⇢ Waste	
☐	Foreground process	→	Reference flow for aggregate production
▨	Background process	→	Reference flow for building level comparison
M	Multifunctional process		

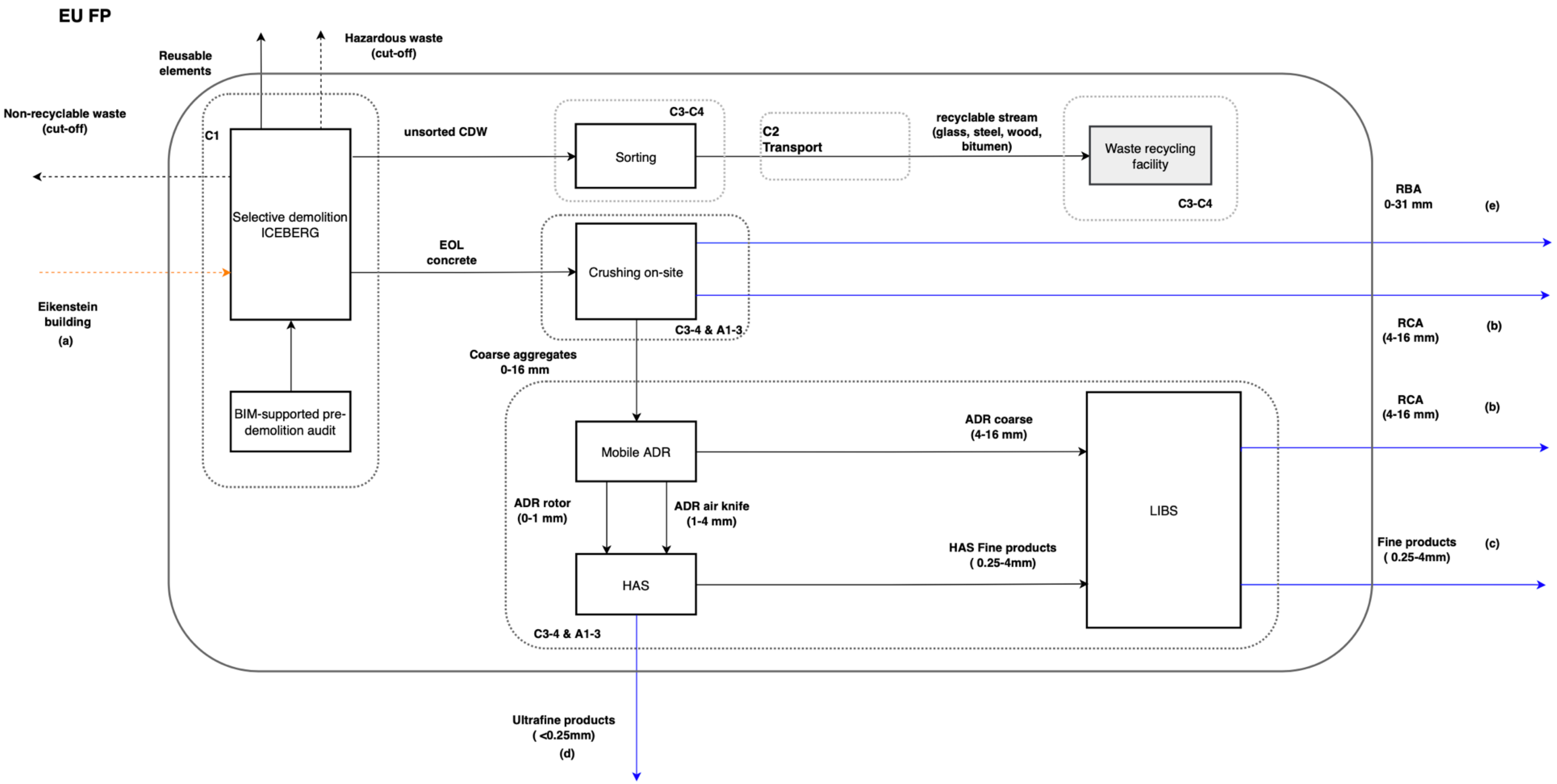


Figure 16. Flow diagram for the product system of the EU FP scenario

Abbreviations

EOL: End of life
CDW: Construction and Demolition Waste
RBA: Road base aggregates
RCA: Recycled Coarse Aggregates
NFA: Natural Fine Aggregates
NCA: Natural Coarse Aggregates

Legend

⬚ System boundary
⬚ EN15804 information module
☐ Foreground process
▨ Background process
M Multifunctional process

→ Good
⇢ Waste
Economic Flows

→ Reference flow for aggregate production
→ Reference flow for building level comparison

4.3.3.1 EU BAU scenario

(a) Demolition

- **Pre-demolition audit**

In the BAU pre-demolition audit, one person from the demolition company visits the demolition site and conducts a quick examination of the interior and exterior spaces, surroundings as well as the location of asbestos to roughly estimate the time and cost to execute the demolition.

- **Pre-demolition and Non-selective demolition**

During the pre-demolition, all the materials are stripped and removed from the building. This process entails using equipment, namely an aerial work platform and hand tools. Five workers, including a skilled operator, complete the process in 320 hours or 40 working days. The derived materials are then sent to a waste management facility. In the non-selective demolition, all the non-stony materials are removed using a demolition crane. This process requires one worker who operates the crane. The materials are transported to a designated facility for waste management. Additional activities such as removing the outer area and pavements are considered part of the non-selective demolition. For the concrete components, a demolition crane and a mobile crusher are employed, and this process results in one large stream of stony materials.

(b) Transport

Trucks with a vehicle capacity of 40 m^3 were used to transport the materials from pre-demolition, the stony and non-stony materials from demolition, and the components collected from the outer area and pavement removal to the designated waste management facilities.

(c) Concrete waste processing: Off-site crushing of mixed stony waste

The mixed stony fraction is transported to a traditional CDW recycling plant (Gálvez-Martos et al., 2018), where the waste streams are separated. Consequently, the stony fractions are crushed into road base aggregates with sizes ranging from 0-31 mm.

(d) Raw material supply

The production of natural coarse and fine aggregates and cement used in producing new concrete is considered.

4.3.3.2 EU BP

(a) Demolition

- **Pre-demolition audit**

Under the current best practices in Europe, the pre-demolition audit entails identifying hazardous substances such as chromium and asbestos. In addition, an estimation of the costs, time, and assembling a list of necessary activities is carried out. Finally, some material streams such as steel or reusable components are noted.

- **Pre-demolition and Selective demolition**

Completing a material inventory by two experts from the demolition company is carried out as part of the selective demolition to roughly list components and materials that can be recycled. These materials are harvested from the building using scaffolding and hand tools during the pre-demolition. In addition, removing obstructive materials such as copper wire and piping with the same equipment is executed. The demolition process is carried out using a demolition crane operated by one worker. As a result, the CDW, ferrous, and wood waste streams are generated.

(b) Transport

Trucks are used to transport the obstructive materials within a 12 km radius to a metal recycling facility. For the CDW, wood, and ferrous streams, trucks with a 40 m3 capacity are employed to allocate the materials to waste management facilities.

(c) Concrete waste processing: On-site crushing of mixed stony waste

From the total mixed stony waste generated from the demolition of concrete components, 100% or 10500 tons are crushed on-site, initially with a crane to sizes ranging up to 500 mm and then with a mobile crusher. This process results in 50% fine and 50% coarse aggregates with sizes from 0-31 mm, that are used as road base aggregates.

(a) Raw material supply

The road base aggregate demand is supplied by the on-site crushing of the mixed stony fraction. The necessary materials, including the natural coarse and fine aggregates and the cement used in the production of new concrete, are supplied by virgin materials.

4.3.3.3 EU FP

(a) Demolition

- **SD-BIM pre-demolition audit**

The pre-demolition audit is carried out using the BIM- aided-Smart Pre-Demolition tool (Figure 17). For this process, two experts from TECNALIA visited the demolition site and performed an audit of the entirety of the building in 8 hours. The audit deliverables include a detailed inventory of the quality, quantity, and location of materials, an optimized plan for potential reuse and recycling of 100% of materials and components, and three-dimensional drawings provided to the demolition company.

Figure 17. BIM-aided-Smart Pre-Demolition equipment used on-site during the demolition of the Eikenstein detention center in May 2022

- **Pre-demolition and Selective demolition**

Following the pre-demolition audit and based on the optimized planning, the sequence of a series of activities comprising the selective demolition is decided. During the pre-demolition, CDW and 18 more waste streams, including wood, glass, ferrous and non-ferrous, linoleum, cable trays, fire extinguishers, and others. Moreover, removing obstructive materials, namely the copper wire and piping, amounts to 24 tons, using scaffolding and hand tools. The reusable materials ranging from doors, toilets, and staircases to bicycle sheds, heaters, insulation (Figure 18), cables (Figure 19), and gratings of air space and others are retrieved at the maximum degree, using the same equipment. Furthermore, the removal of the outer area, including the fencing, gates, light poles, and pavements, is performed with a demolition crane. In total, the man hours dedicated to the EU FP pre-demolition and demolition were double compared to the EU BAU and EU BP scenarios. In addition, the total amount of the generated CDW from the ICEBERG pre-demolition and selective demolition is approximately 70% and 35% less than the EU BAU and EU BP demolitions, respectively.

Figure 18. Collection of insulation materials (photographed by Frank Rens and Bente Kamp, GBN)

Figure 19. Collection of cables (photographed by Frank Rens and Bente Kamp, GBN)

Figure 20. Stripped area, collection of doors and cable trays (photographed by Frank Rens and Bente Kamp, GBN)

The main demolition event is executed by a demolition crane operated by two workers in 360 hours. The generated waste included CDW, wood and ferrous waste streams, and contaminated stony material. For the EOL concrete, a demolition crane is used for a total of 320 working hours. From this process, 10500 tons of stony material were generated.

Figure 21. Stony waste

Figure 22. Mixed waste before separation

(b) Transport

Trucks were used to transport the obstructive materials within a 12 km radius to a metal recycling facility. For the CDW, wood, and ferrous streams, trucks with a 40 m3 capacity were employed to allocate the materials to waste management facilities. The transportation of the harvested materials for reuse or recycling was carried out by the local market stakeholders, who also collected them by dismantling on-site.

(c) Concrete waste processing: concrete recycling

The processing of stony material and concrete waste generated from the selective demolition was done in three different ways. During the concrete demolition, 10500 tons of stony material and concrete rubble were generated. It is assumed that approximately 30% of the total amount was of lower quality and thus was crushed on-site to produce road base and concrete aggregates. In detail, 1500 tons were crushed into RBA. Consequently, the remaining 9000 tons of stony material could be further processed into concrete aggregates. Specifically, 20% or 1800 tons were crushed on-site into clean coarse aggregates for concrete production. The other 70% or 7200 tons of stony material was further processed and crushed to sizes 0-16mm. These fractions became the input for the C2CA technology to produce coarse and fine aggregates for new concrete production.

- **On-site crushing**

The on-site crushing entails reducing the size of EOL concrete to 0-16mm, which will then become an input for HAS. In addition, 20% of the concrete fractions that amount to 1800 tons are first crushed to 0,5 m with a pulverizer attachment to the crane for demolition and then crushed into clean coarse aggregates for concrete production. Finally, the stony waste is crushed to 0-31 mm for road base aggregates. A mobile crusher carries out both processes.

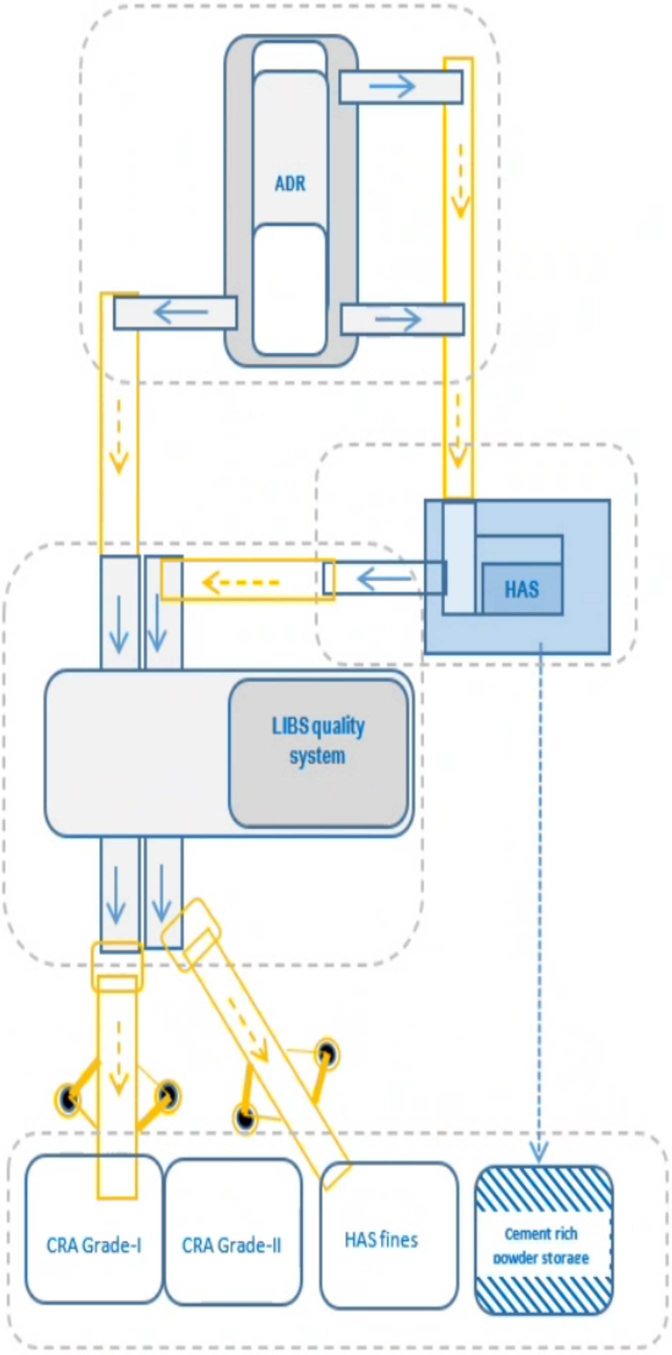


Figure 23. C2CA facility on-site (provided by Frank Rens, GBN)

(a) Raw material supply

- **ICEBERG technologies**

Ideally, C2CA technology (ADR, HAS), and LIBS would be in the same location and preferably on-site (Figure 23). In reality, ADR and HAS are currently located in Hoorn, approximately 100 km from the demolition site. In addition, LIBS is at the TU Delft lab in Delft, which is also a 100 km distance from Zeist, where the demolition is taking place. However, for the EU FP scenario, it is assumed that all the equipment is on-site.

- **ADR**

The crushed concrete waste with sizes 0-16 mm produced by the on-site crushing with a mobile crusher is fed into ADR. A spinning rotor that breaks grain bonds and an air shifter that separates the coarse from the fine fractions are the two major parts of ADR(Gebremariam et al., 2020a). The crushed concrete is sorted into three streams: the ADR air knife with a size of 1-4mm, the ADR rotor smaller than 1 mm, and the ADR coarse with a size of 4-12mm. Overall, coarse, and fine aggregates account for 70% and 30% of the concrete waste feed that enters HAS. In addition, the fine fractions contain wood and plastic contaminants. The ADR technology operates on diesel and lubricating oil.

- **HAS**

The fine products from ADR, namely the ADR air knife (1-4 mm) and the ADR rotor (<1mm), enter HAS, which has a complementary setup to ADR (Gebremariam et al., 2020a), as seen in Figure 23. Gebremariam et al. (2020) reported that several components, including a burner, vibrator motors, a compressor, rotary sluice, and a cyclone, are part of the HAS set-up. The sequence of heating and cooling is used to classify particles based on their size to produce fine aggregates (HAS fine products) and ultrafine cement components (Gebremariam et al., 2020) that amount to 80% and 20% of the feed entering HAS. The primary input for the HAS system is biodiesel, used in the burner component as a heat source.

- **LIBS**

LIBS is a quality sensor that evaluates the quality of the ADR coarse (4-16mm) and the HAS fine products (0,25- 4mm). After the assessment, the products are labeled with all the relevant information about the aggregate quality, including composition and compressive strength. The LIBS setup is relatively simple, entailing a short laser pulse inside a commercial container with two conveyor belts on which the aggregates are deposited. It can be constructed in a new location within a day.

4.3.4 Data quality

The product systems defined for each scenario or alternative were assessed within the LCA and LCC integrated framework. Overall, the data collection for this project is multilevel, ranging from case, sector, and application-specific to generic, and was carried out collectively for LCA and LCC. The transport, materials, labour, and machinery inputs for each unit process of every scenario were considered. In addition, the data are classified as primary and secondary. The primary data were measured and collected within the ICEBERG case study, while the secondary data were estimated. Thus, their level of quality ranges from sector-specific, application-specific, to generic.

Additionally, the direct and indirect environmental emissions were derived from the Ecoinvent 3.7.1 database, which is embedded in the Activity Browser software. Finally, it is imperative to acknowledge the importance of expert opinion from actors within the construction sector involved in the ICEBERG project that provided explanations and clarifications for the decision-making on-site and the motivations behind it. The primary data were collected in the context of the ICEBERG case study and are case-specific, provided by Frank Rens and Bente Kamp (GBN), that supervised the demolition project on-site.

Table 11. Overview of the primary data for the integrated LCA-LCC

Category	Primary data (from GBN)	Level
Demolition	All activities and material inputs, man-hours spent to dismantle	Measured, case-specific for the demolition of the Eikenstein detention center
Machinery	Type and model, installed power, operation hours, type, and volume of consumed fuel	
Waste management	Measured retrieved quantity or weight, destination business or facility for reuse/ recycling	
Transportation profiles	All transport requirements from site to waste management facilities	
Costs	Rental or purchasing cost for all machinery, labour, freight costs	

For the EU BAU and EU BP that are based on virtual demolitions, it was assumed that the same equipment was used for all the demolition activities.

In addition, reference values on the quantity of the retrieved material, the waste management options, and the man-hours spent on the project were estimate by the field experts, involved in the demolition project. These values are classified as secondary data on a case-specific level. Other types of information, such as infrastructure or energy production processes, were acquired from Ecoinvent 3.7.1 database accessed through AB.

4.3.5 Multifunctionality and allocation

A system expansion approach was adopted to avoid the multifunctionality of processes in the product systems. Firstly, processes were detailed into sub-processes within the system boundary to account for the relevant inputs and outputs. In addition, the system boundaries were expanded to include the production of natural coarse and fine aggregates as well as the production of cement in the EU BAU and EU BP scenarios. This approach entails adding extra functions to the functional unit, as explained in section 4.2.

4.3.6 Results of inventory analysis

The inventory analysis results for LCA, including elementary flows for the product systems under analysis, can be found in Appendix C, that was submitted as an Excel file. For LCC, the full economic inventory, including costs grouped based on the EN 15804 module, by type and stages can be found in Appendix D.

4.5 Impact assessment

4.5.1 Impact categories

The impact categories were selected per the goal and scope of the study to present a set of relevant environmental issues. A complete impact assessment allows for the comparison of the three alternatives as well as the identification of hotspots in their respective lifecycles. The ReCiPe impact assessment method was selected as a baseline as it offers characterization factors at the midpoint level that can underline eminent environmental issues (e.g., water depletion, particulate matter formation). In addition, an additional impact assessment will be carried out under a combination of selected impact categories from the CML 2001 impact assessment method to perform a sensitivity analysis (see section 4.6.4).

4.5.2 Classification

Based on the ISO definition, the classification process entails assigning the LCI results to impact categories according to their potential contribution to every impact category. Moreover, the elementary flows relevant to the impact categories within the ReCiPe impact assessment method are enlisted during classification, which AB carries out.

4.5.3 Characterization results

The characterization results for the ReCiPe impact assessment method can be found in tabular form in Appendix D. In Figure 25, the characterization results are presented relative to the alternative with the largest indicator result, scaled to one.

In most impact categories, the EU FP alternative performs better than the EU BAU and EU BP, which present similar performance across all the impact categories. In the metal depletion, natural land transformation, and ozone depletion impact categories, the EU FP alternative has the higher impacts. The most significant difference in values between the alternatives is observed in the climate change impact category, in which the EU FP has a 50% lower impact compared to the EU BAU, which is the alternative with the largest indicator result.

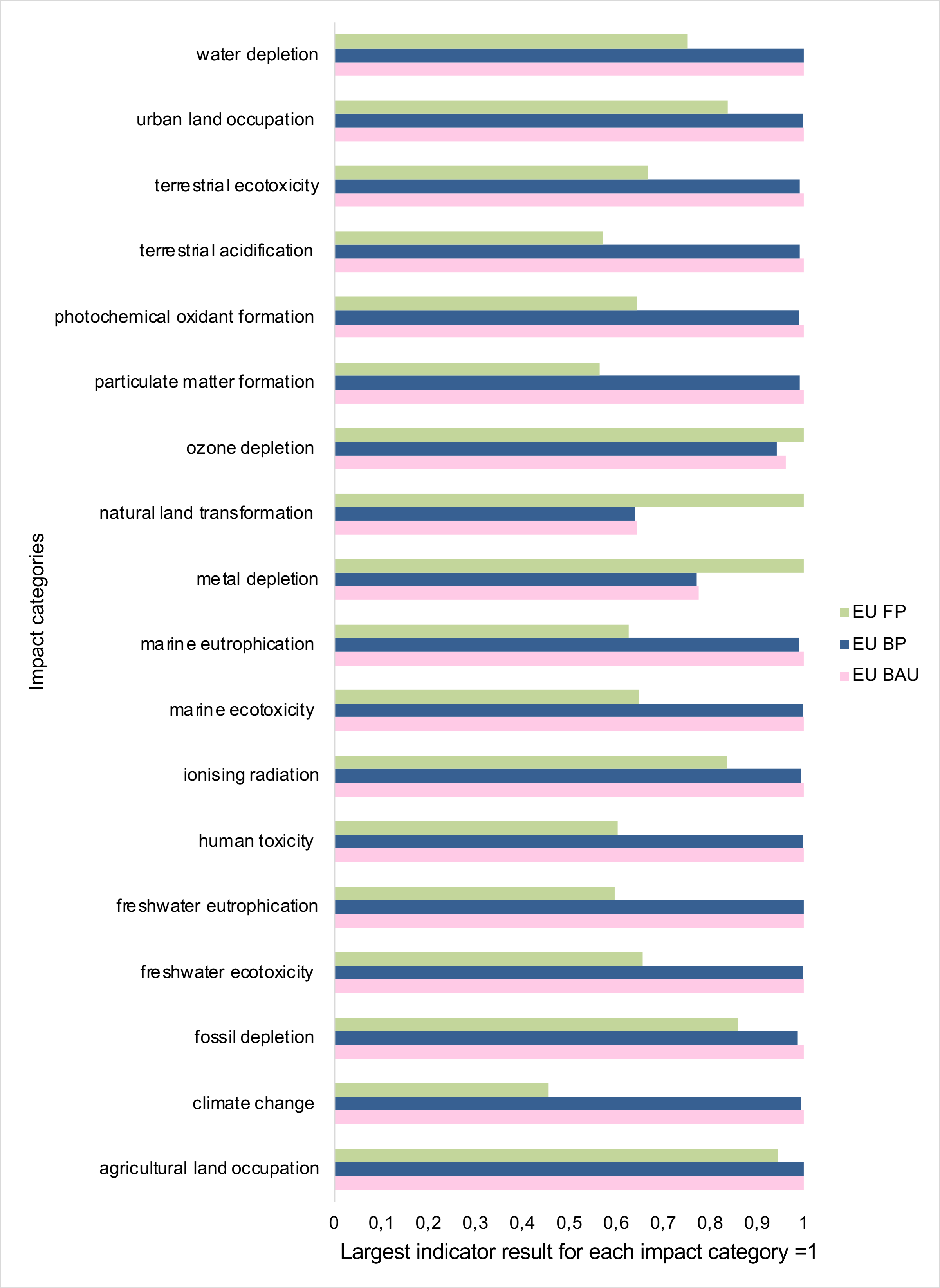


Figure 24. Characterization results for ReCiPe impact categories, relative to the largest alternative=1

4.5.3.1 LCC results

Overall, the costs associated with the EU FP are lower than the EU BP and EU BAU product systems, with the latter illustrating higher costs. The positive and negative values indicate economic costs and profits, respectively.

In the EU BAU, the higher cost is attributed to the materials category, which includes processing fees for waste management, such as CDW, and the material supply of NCA, NFA, and cement. The transportation costs are one of the lowest contributors to cost, similarly to the other scenarios. Nevertheless, a significant amount of RBA is assumed to be sold to an infrastructure project nearby. However, the transportation is carried out by the external partners that purchased the materials and are not included in the total costs.

The labour costs are the lowest compared with the EU BP and EU FP scenarios. This result was anticipated because non-selective demolition is less time-consuming, and thus, fewer working hours are required to be completed. At the same time, fewer materials are harvested for recycling; therefore, the proceeds are also lower and solely result from the recycling of ferrous materials.

In the EU BP, where selective demolition is carried out, the labour costs are increased since more working hours are required for the pre-demolition and demolition process. Consequently, more materials are harvested, and the proceeds from the recycling of ferrous and non-ferrous materials are higher compared to the EU BAU scenario.

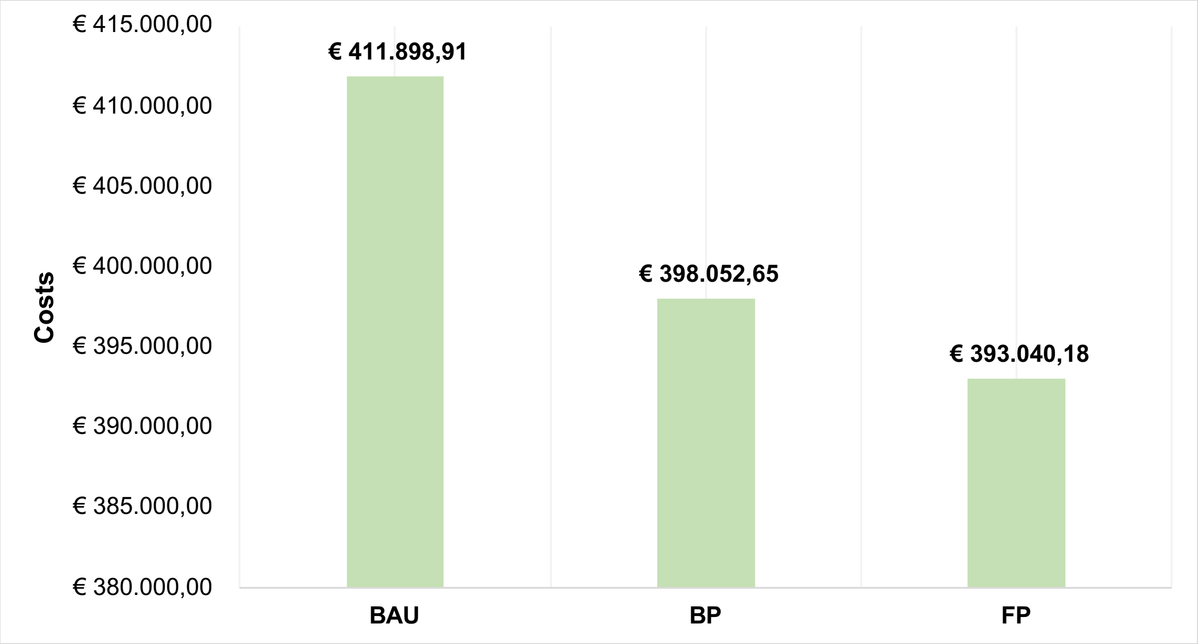


Figure 25. Comparative overview of total costs for EU BAU, EU BP, and EU FP scenarios

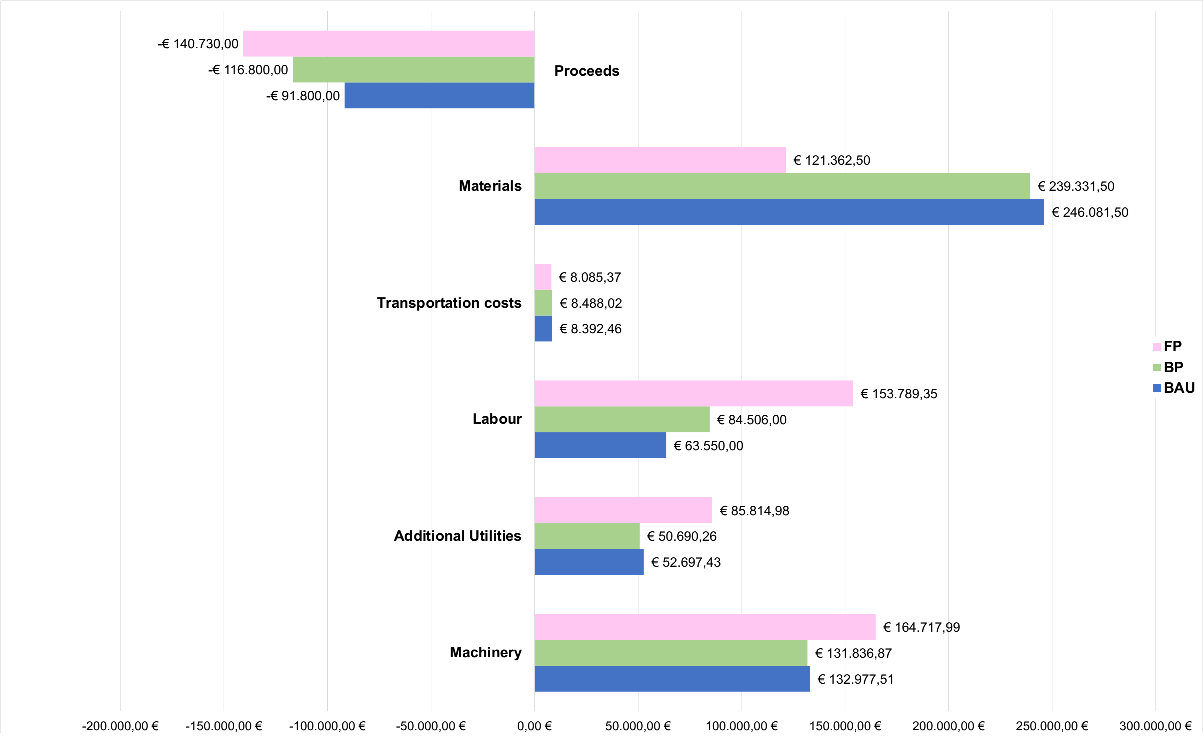


Figure 26. Comparative economic profile for the EU BAU, EU BP, and EU FP scenarios

As seen in Figure 26, for the EU FP, the costs for labour, additional utilities that include diesel for machinery, lubricating oil, and fuel for transportation as well as machinery are 142%, 63%, and 24% higher, respectively, compared to the EU BAU. However, since less waste is produced from demolition and more materials for reuse and recycling are harvested in this scenario, the cost for materials, including waste processing, is 50% lower, and the proceeds from reuse are 35% higher than the BAU. Overall, the difference in total costs for the three alternatives is considerably small, with a maximum of 5% difference between the BAU and FP scenarios.

4.6 Interpretation

4.6.1 Consistency check

In this section, the consistency of the methods, data, and assumptions will be addressed concerning the goal and scope of the study, as described in section 4.1. The background processes included in the product system and linked to the foreground processes were retrieved from the Ecoinvent 3.7.1 database in all three alternatives. All the background and foreground processes modeled in the product systems can be found in Appendix C. Moreover, as explained in Section 2, the data sources that detail how practices such as pre-demolition audits, demolition, and concrete processing were carried out for the EU BAU and EU BP scenarios are literature-based. At the same time, the EU FP is based on the Eikenstein case study. In addition, all scenarios were developed based on reference numbers derived from the case study (e.g., the total amount of stony waste). However, estimations were made for the amount of EOL concrete fractions diverted to downcycling as road base aggregates and to recycling as clean coarse aggregates, reflecting the practices portrayed in each scenario. All estimations regarding waste management options resulted from communication with experts from the construction sector involved in the Eikenstein demolition project. In terms of technology coverage, the technologies, including on-site crushing of aggregates or treatment of CDW in a traditional recycling plant for the EU BAU and EU BP scenarios, are existing large-scale technologies. On the other hand, ADR, HAS, and LIBS in the EU FP scenario are recently developed. Finally, the geographical coverage of the scenarios is the same since the Netherlands was used as a representative technology mix for the EU-27 MS.

4.6.2 Completeness check

The data completeness and level of detail are identical for all alternatives, in alignment with the system boundary as presented in section 4.1. The cut-offs made were the same for every product system. In addition, the results are similar to previous research on selective demolition and aggregate production of standard concrete. Moreover, in the Hiser project, the impacts of the best practice scenario, which entailed selective demolition and use of the ADR equipment for processing aggregates, similarly to the EU FP scenario of this study, were more significant in the ozone layer depletion impact category. In addition, cement was identified as the highest environmental burden among concrete ingredients.

4.6.3 Contribution analysis

The contribution analysis for the LCA was performed within AB, combining the process contributions and Sankey diagram tabs for each impact category and alternative. This analysis is carried out on the process level, starting from the reference flows within the basket of functions for each scenario and moving upstream to determine background processes contributing to the cumulative impacts. Each alternative's results are illustrated separately to determine which processes have the highest contribution in the respective scenarios. In addition, a comparative analysis was performed for the climate change impact category, which presents the higher value difference among the three systems to pinpoint which processes have the highest contribution.

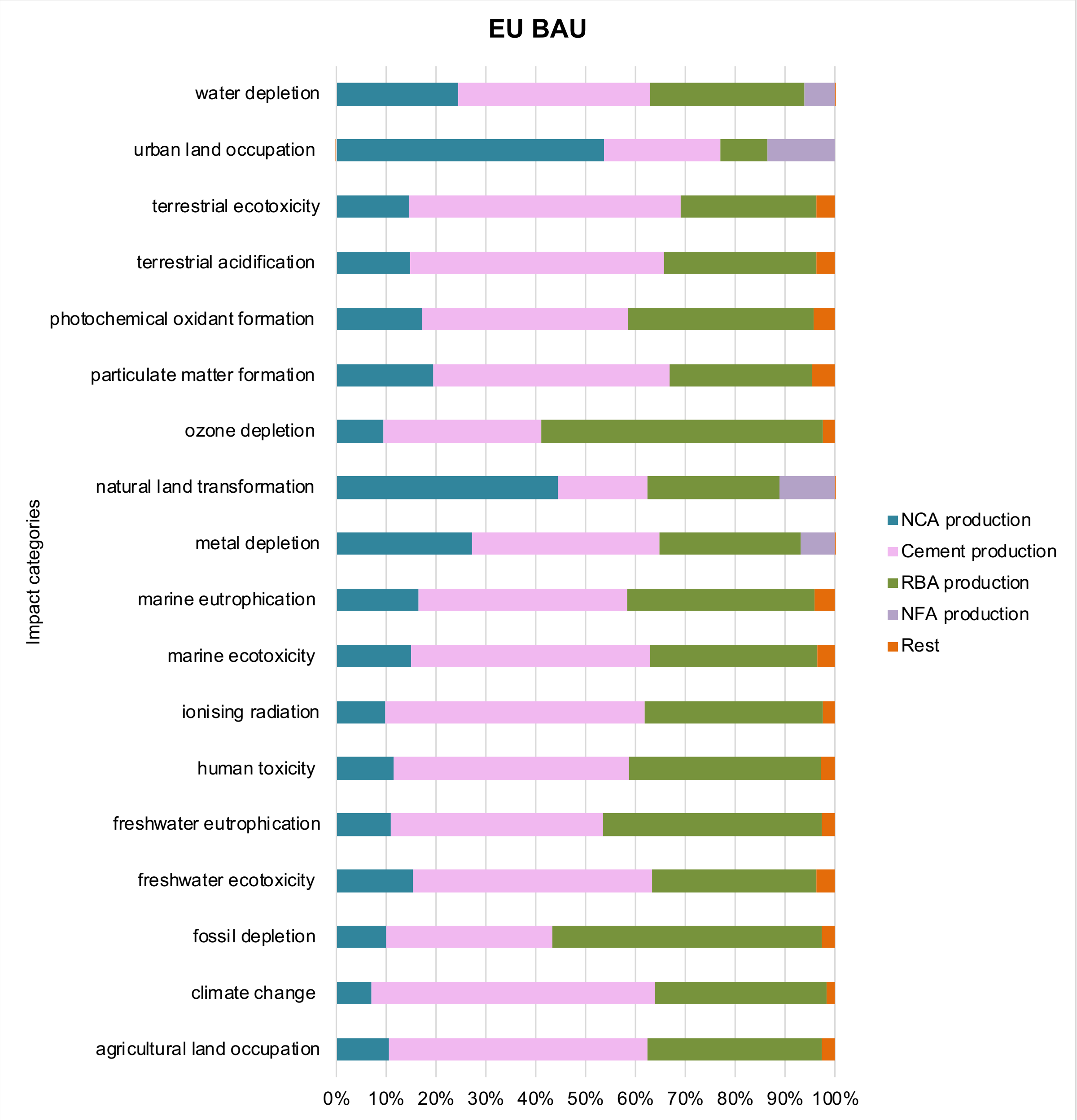


Figure 27. Contribution analysis results for the EU BAU scenario

For the EU BAU scenario, the cement production process is the highest contributor in all impact categories. Moreover, the climate change impact category contributes 57% of the total impacts. In addition, for terrestrial ecotoxicity, agricultural land occupation, ionizing radiation, and terrestrial acidification, over 50% of the absolute magnitude of each impact category is a result of cement production. Looking deeper into the background system associated with cement production, clinker and granulated blast furnace slag production processes add to the cumulative impact of cement. Its lowest contribution is observed in the natural land transformation category at 18%, in which the production of NCA dominates the share of impacts with 44%. The NCA production, which entails the gravel and sand quarry operation, has the highest percentage of impacts, reaching 54% in the urban land occupation and the lowest at 7% in the climate change impact category. The second highest contributor in most impact categories is the RBA production, with 56% and 54% contribution in ozone and fossil depletion impact categories.

Machinery such as demolition cranes and mobile crushers for treating aggregates are prominent equipment used in RBA production. They entail electricity and diesel as inputs for their operation, resulting in considerable impacts.

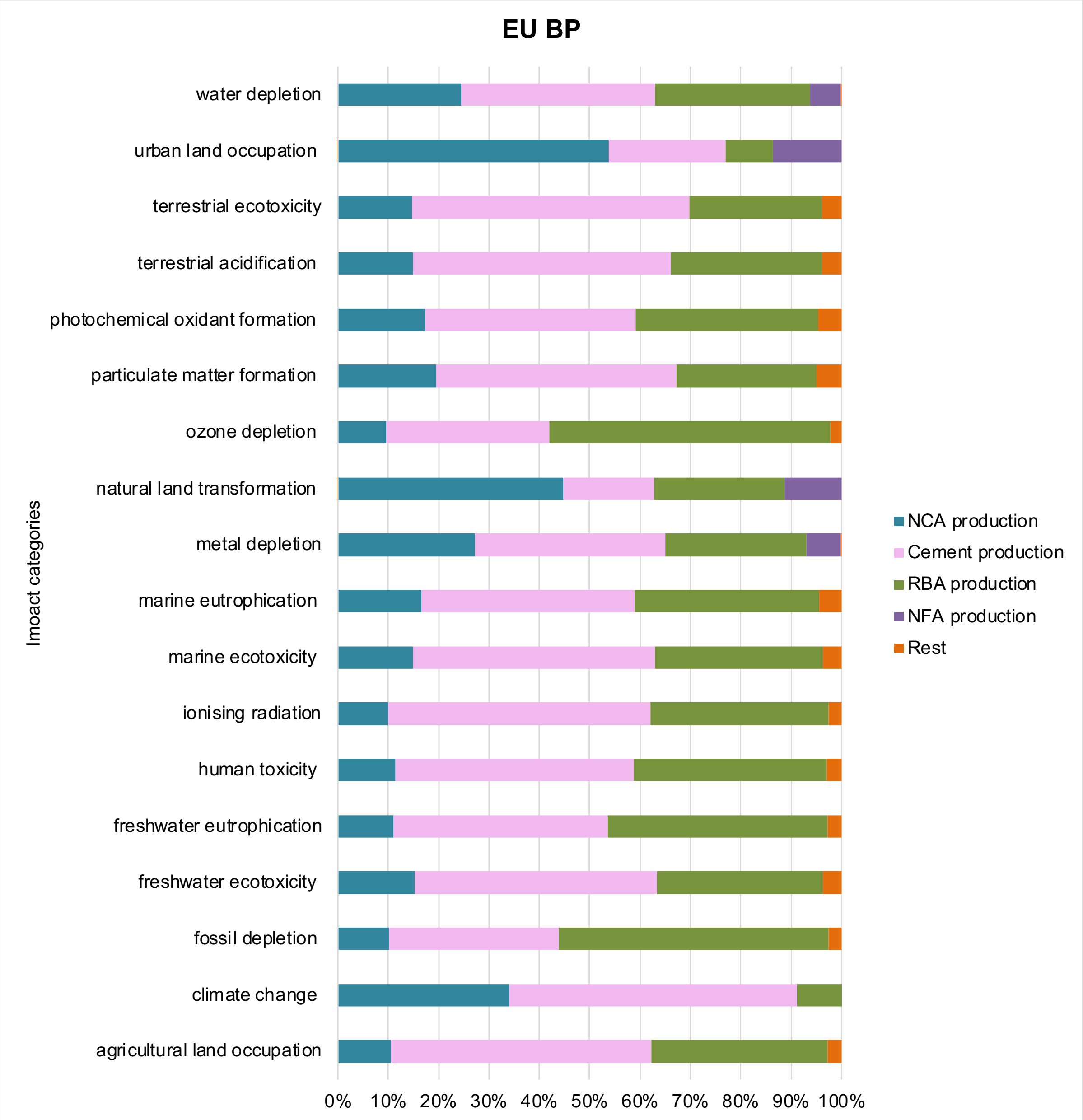


Figure 28. Contribution analysis results for the EU BP scenario

Despite its better performance in terms of absolute impacts, the EU BP contribution analysis results present high similarity compared to the EU BAU scenario. That was anticipated since many processes are common in the two alternatives. Moreover, cement production is the main contributor across all categories, with impacts originating from clinker and granulated blast furnace slag production processes, contributing over 40% to 14 of the 18 impact categories. Overall, the NFA production, which entails the gravel and sand quarry operation, similarly to the NCA production, has the overall lowest contribution with a maximum of 14% in the urban land occupation impact category.

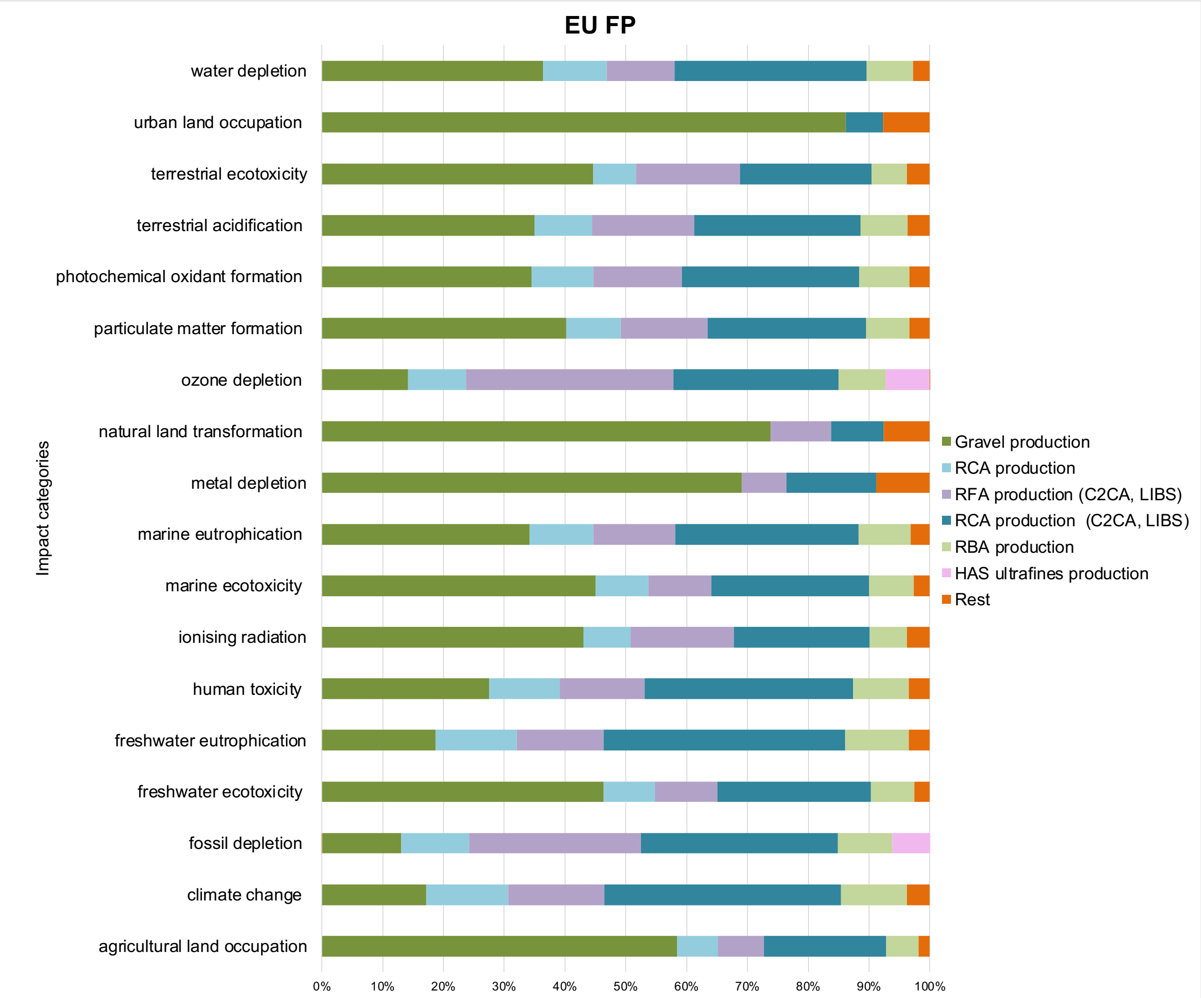


Figure 29. Contribution analysis results for the EU FP scenario

For the EU FP scenario, crushed gravel production is the highest contributor in 13 out of 18 impact categories. This process is an Ecoinvent background process used as a proxy to accommodate the demand for 9000 tons of RBA. In urban land occupation, its contribution reaches 86% of the total magnitude and is related to background processes regarding infrastructures, such as gravel and sand quarry construction. In agricultural land occupation, metal depletion, and natural land transformation, gravel production dominates over 50% of the share of impacts. Various processes associated with heavy machinery operation, diesel consumption, electricity production processes, and infrastructure are connected with gravel production and thus contribute to its impacts. The RCA production, combined with the C2CA and LIBS technologies, contributes 32-40% to climate change, freshwater eutrophication, human toxicity, and fossil depletion categories. These impacts are associated with background electricity, diesel production, and machine operation processes.

As seen in the characterization results in Section 4.5.3, the EU FP alternative has the highest absolute impacts in the metal and ozone depletion and natural and transformation categories. Interestingly, the highest contributor in 2 out of 3 categories, namely metal depletion and natural land transformation is the gravel production process, added in the EU FP scenario as part of the system expansion method, which accommodates modeling the three scenarios comparatively. In the ozone depletion impact category, the RFA production has the highest contribution at 34%, resulting from background production processes for diesel, which is used as fuel. However, it is essential to note that, in reality, the fuel used in this process is hydrotreated vegetable oil. This could have affected the results and presented a point of improvement for further research.

As mentioned previously, the climate change impact category presented the highest difference in terms of absolute impacts among the three alternatives, with the EU FP having approximately 50% lower impacts than the other alternatives. A contribution analysis on a process level in relative share was performed for the climate change impact category to determine the reasons behind this significant difference. As seen in Figure 30, one of the top three contributors in the EU FP scenario is the machine operation process. This Ecoinvent background process was used as a proxy for the demolition crane and mobile crusher equipment. In addition, electricity production and diesel burned as fuel for the machinery are also contributing to the total impacts of the EU FP for this category. For the EU BAU and EU BP alternatives, the highest contributor on a process level is clinker production, a well-known material used for cement production. Furthermore, machine operation, diesel as machinery fuel, and electricity production are among the top contributors in the climate change impact category for both alternatives.

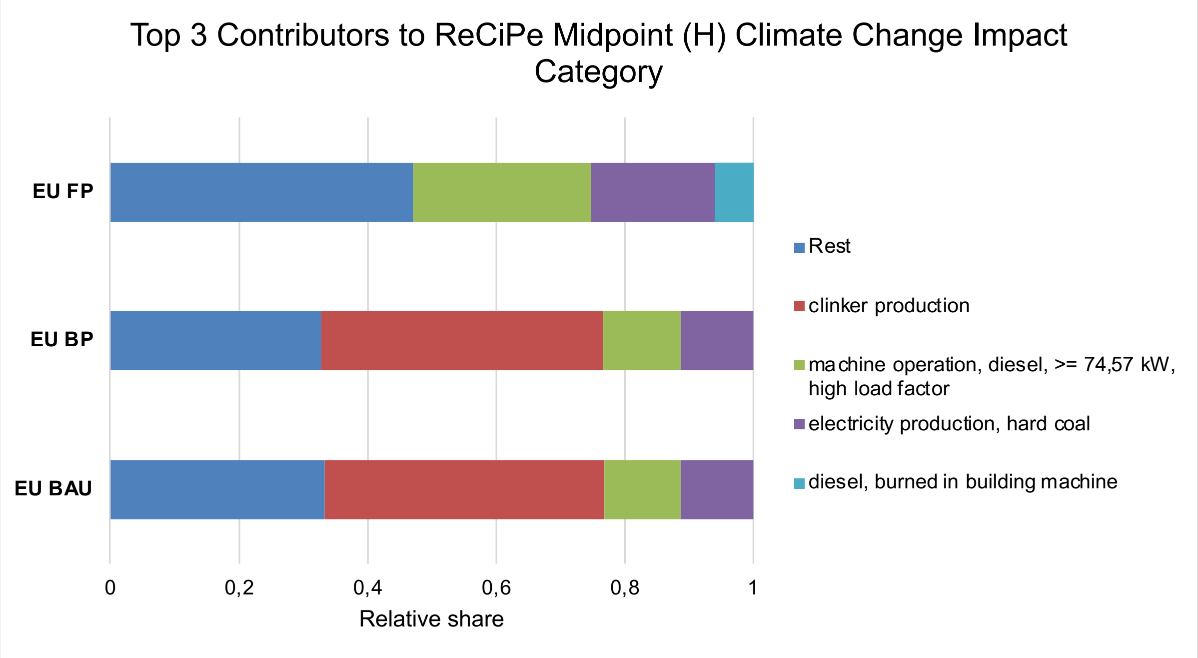


Figure 30. Contribution analysis results for the climate change impact category

In addition, as described by Zhang et al., (2019), even though lower total cost signifies a better economic performance, the breakdown of costs (Figure 31) is essential to identify financial hotspots for each alternative. For the EU BAU, 60% of the costs occur from the materials category, which entails processing fees for waste management and the supply of building materials. As anticipated, the produced waste is higher in the EU BAU scenario because demolition is carried out non-selectively. Transportation costs have the lowest contribution to the total costs. This results from the assumption that external partners transport the RBA to an infrastructure project nearby, similar to the ICEBERG case study. However, in previous research, transport has been identified as a hotspot for environmental impacts. Therefore, a sensitivity analysis will examine how this assumption affected the results.

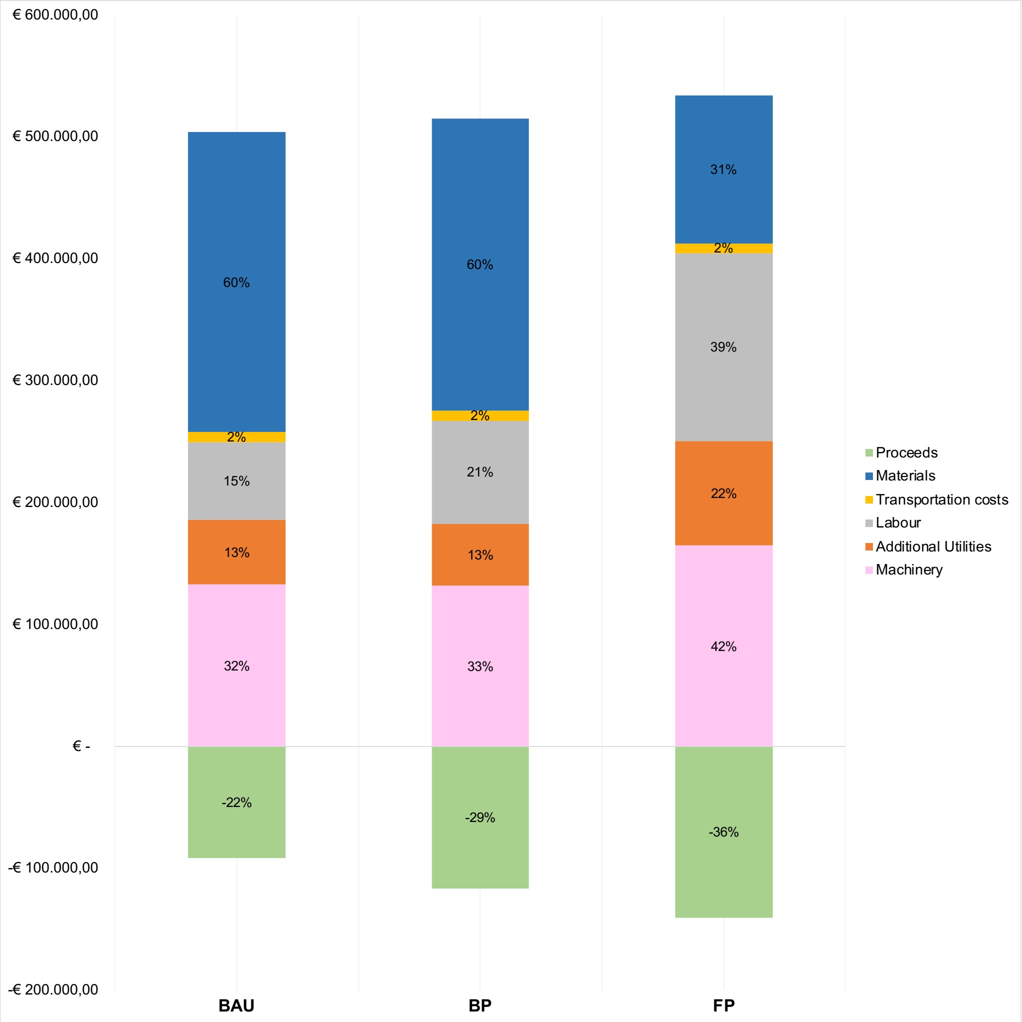


Figure 31. LCC contribution analysis for the EU BAU, EU BP, and EU FP scenarios

Similarly, in the EU BP, the highest contributor is the material category, followed by machinery. Labour is the third highest contributor to costs with 33%. Compared to the BAU, labour and proceed categories amount to approximately the same share of costs in the respective scenarios. However, in absolute terms, as seen in Section 4.5.3, labour and proceeds are higher in the EU BP alternative. This is because additional man hours are allocated to selective demolition, leading to higher labour costs. At the same time, it results in a significant amount of recycled materials, ultimately leading to higher profits.

In the EU FP alternative, machinery is the highest contributor at 42%, which is explained by the longer operation hours spent on-site to carry out selective demolition. Furthermore, along with additional operation hours for machinery, selective demolition requires more man-hours from workers for harvesting materials from the building and operating the heavy machinery on-site. This results in the labour category accounting for 39% of total costs in the EU FP scenario, while at the same time, a reduced amount of CDW is diverted to waste treatment. Consequently, more components are acquired for reuse and recycling. The proceeds from selling the harvested components to partners from local markets result in a higher profit than the other two alternatives in absolute terms and a higher share in the breakdown of costs for the EU FP scenario.

4.6.4 Sensitivity analysis

(a) Characterization family

To assess the degree to which the results were affected by the ReCiPe impact assessment method selection, a set of similar impact categories from the various impact assessment methods were selected to perform the sensitivity analysis.

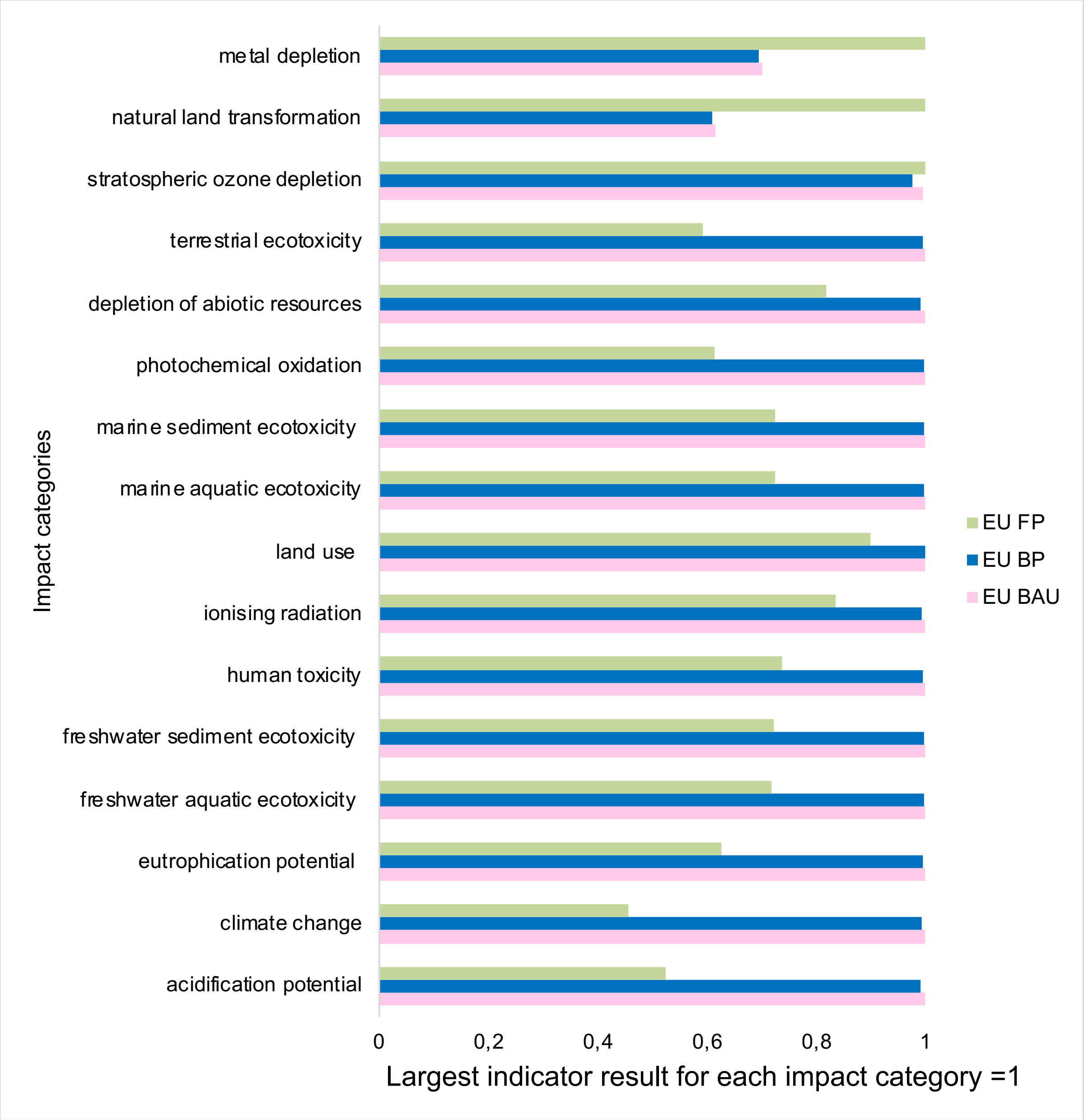


Figure 32. Sensitivity analysis (SA) results for a selection of CML 2001 impact categories, relative to the largest alternative=1

Similar to the ReCiPe baseline results, the EU FP scenario performs better in most impact categories, while the EU BAU and EU BP showcase similar performance. It is essential to mention that the EU FP presents higher impacts in the ozone depletion, metal depletion, and natural land transformation impact categories, consistent with the ReCiPe baseline results.

(b) Location of concrete recycling facility

The ADR, HAS, and LIBS equipment was assumed to be located on-site in the EU FP scenario even though, in reality, they were situated in Hoorn and the TU Delft lab; thus, the aggregates could possibly be transferred to these locations. The assumption for the on-site processing was made based on the fact that mobile versions of the ADR and HAS are available while LIBS can be set up on location within a day. The extent to which this assumption affected the results will be assessed through sensitivity analysis entailing the actual transportation distances.

The sensitivity analysis entails adding two processes in the EU FP product system, specifically, loading 7200 tons of aggregates that will be processed with the C2CA technology and LIBS to respective containers on-site and their transportation by lorry to an off-site facility located 100 km from the demolition site in Hoorn.

As anticipated, this adjustment results in increased impacts, reflected in the impact category results for the EU FP scenario in Table 12. Moreover, the highest increase in impacts, ranging up to 83% compared to the baseline analysis, was identified in the terrestrial ecotoxicity impact category, resulting from increased brake wear emissions from the freight transport of the aggregates with a lorry. In addition, the 34% and 27% increase in the ozone and fossil depletion categories are attributed to background processes associated with diesel production processes used as fuel.

Table 12. Sensitivity analysis (SA) results for EU FP scenario

Impact categories	Unit	Baseline	SA	Difference (%)
		EU FP	EU FP	
Agricultural land occupation	square meter-year	7,43E+03	7,88E+03	6%
Climate change	kg CO2-eq	1,80E+05	2,44E+05	26%
Fossil depletion	kg oil-eq	7,05E+04	9,65E+04	27%
Freshwater ecotoxicity	kg 1,4-DCB-eq	2,57E+03	2,96E+03	13%
Freshwater eutrophication	kg P-eq	4,97E+01	5,40E+01	8%
Human toxicity	kg 1,4-DCB-eq	4,25E+04	6,32E+04	33%
Ionising radiation	kg U235-eq	2,32E+04	2,86E+04	19%
Marine ecotoxicity	kg 1,4-DCB-eq	2,31E+03	2,91E+03	21%
Marine eutrophication	kg N-eq	2,32E+02	2,81E+02	17%
Metal depletion	kg Fe-eq	1,26E+04	1,47E+04	14%

Natural land transformation	square meter	1,80E+02	2,07E+02	13%
Ozone depletion	kg CFC-11-eq	2,47E-02	3,72E-02	34%
Particulate matter formation	kg PM10-eq	2,44E+02	3,52E+02	31%
Photochemical oxidant formation	kg NMVOC	7,02E+02	9,03E+02	22%
Terrestrial acidification	kg SO2-eq	5,83E+02	7,40E+02	21%
Terrestrial ecotoxicity	kg 1,4-DCB-eq	8,56E+00	5,14E+01	83%
Urban land occupation	square meter-year	4,98E+03	1,15E+04	57%
Water depletion	cubic meter	6,38E+02	6,89E+02	7%

In comparison to the EU BAU and EU BP scenarios, as illustrated in Figure 33, the results present a shift compared to the baseline results, with the EU FP scenario having higher impacts in 8 out of the 18 categories. Apart from the ozone depletion, metal depletion, and natural land transformation, the urban land occupation, terrestrial ecotoxicity, ionizing radiation, fossil depletion, and agricultural land occupation impact categories have been added to the list of categories in which the EU FP showcased the highest impacts during the baseline analysis.

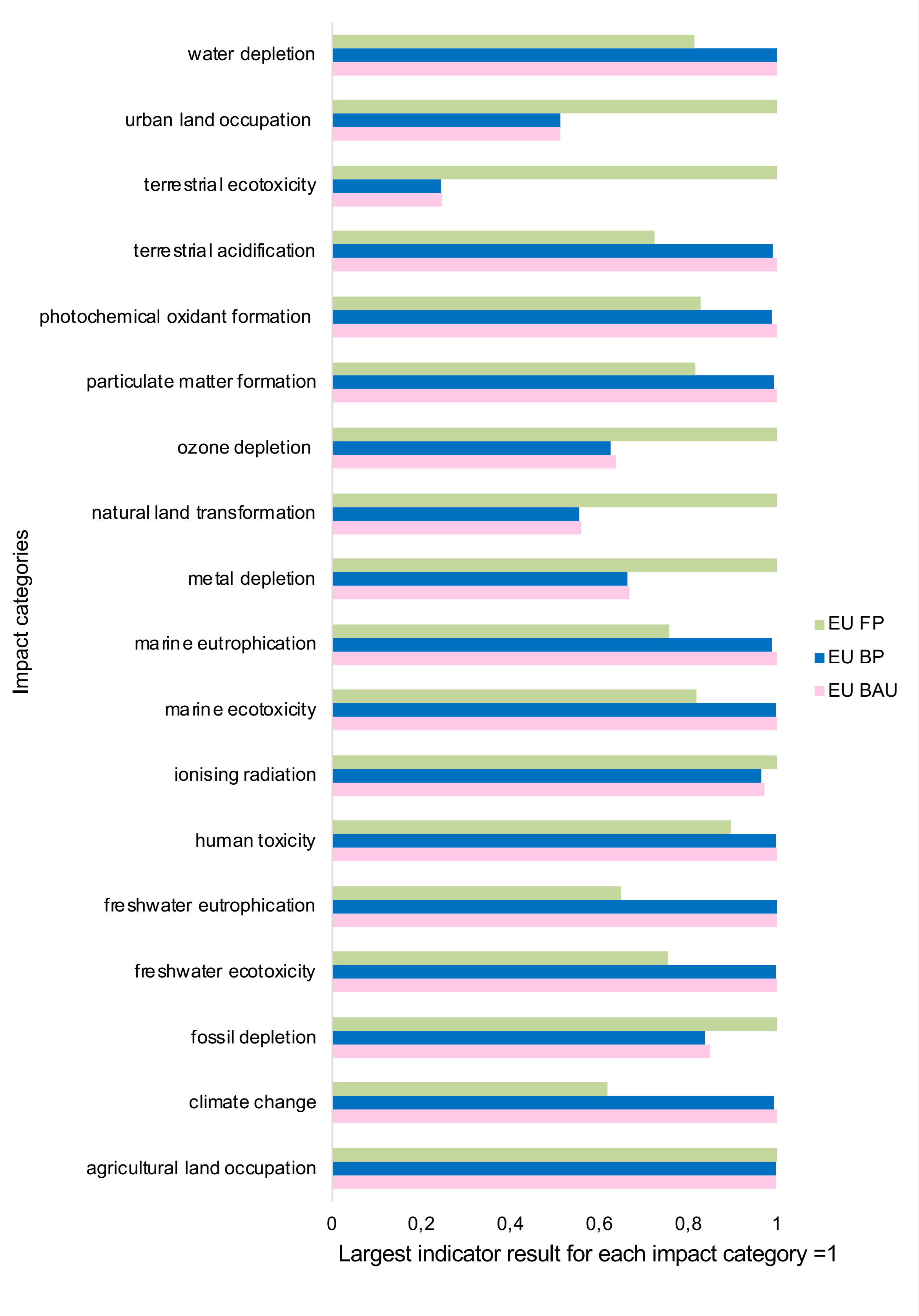


Figure 33. Sensitivity analysis results for ReCiPe impact categories, relative to the largest alternative=1

Although the EU BAU still dominates most impact categories from an environmental standpoint, the landscape in the economic analysis has changed. The additional costs for loading and transporting the aggregates from Zeist to Hoorn result in an 87% increase in transportation costs and a 2% increase in utilities attributed to the increased fuel consumption by the machinery used to load the aggregates for transportation on-site (Figure 35). Overall, the additional transportation of aggregates resulted in a 10% increase compared to the baseline results for the total costs and higher overall costs for the EU FP scenario (Figure 34).

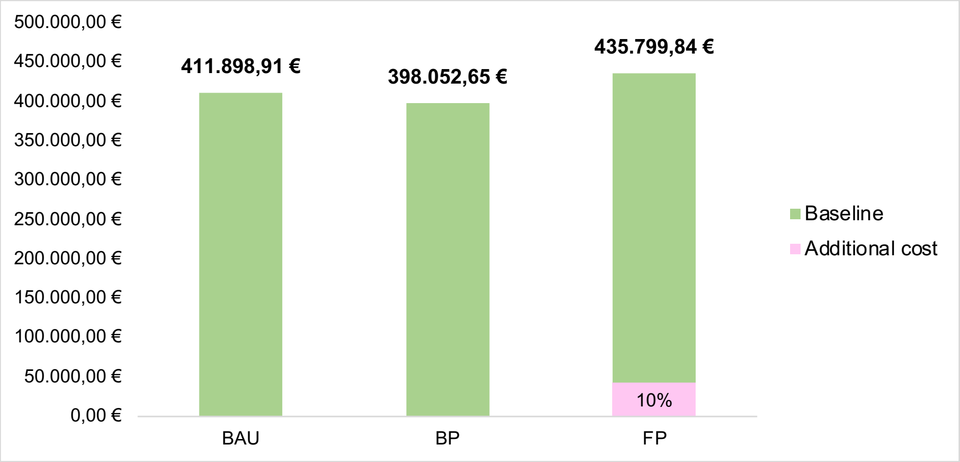


Figure 34. Comparative overview of total costs for EU BAU, EU BP, and EU FP scenarios

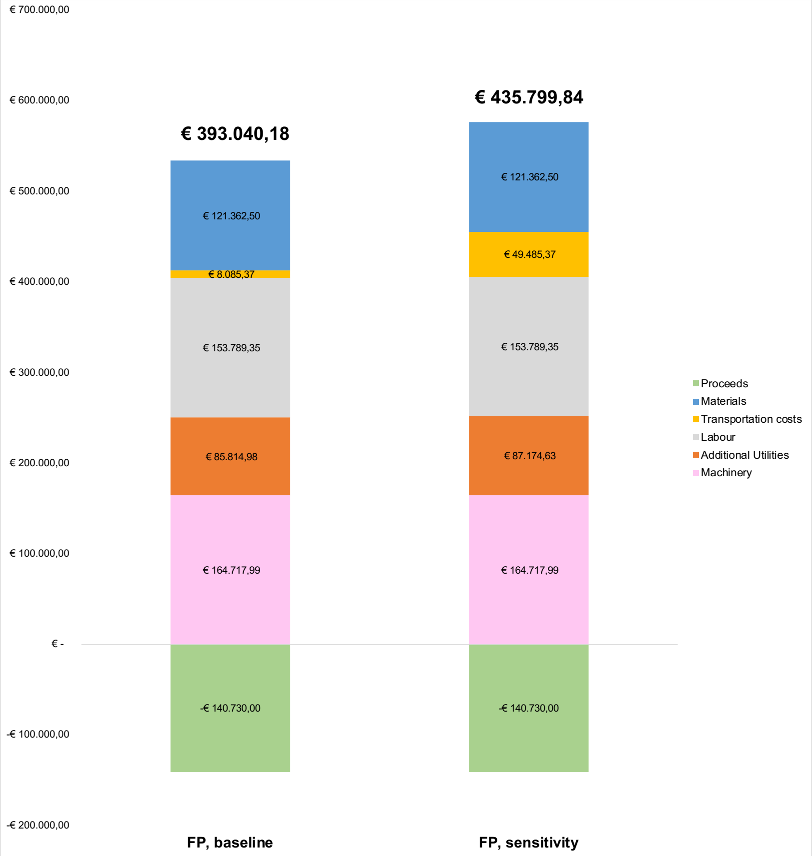


Figure 35. Comparative economic profile for the EU FP baseline and sensitivity analysis results

(c) Transportation of RBA to infrastructure project

In the ICEBERG case study, the transportation of the RBA that was sold to an infrastructure project was carried out by external partners. Based on that information, it was assumed that the transport of RBA in all the alternatives is carried out similarly; thus, it was not considered part of the product systems.

However, because that might not be the case in most European projects and since transport has been identified as a hotspot in previous research on concrete recycling, transport of the RBA was modeled as part of the sensitivity analysis for the three alternatives.

Moreover, in the EU BAU, the transportation of 10500 tons of RBA to the facility at a 40 km distance, in the EU BP, the transportation of 10500 of RBA to the facility at a 20 km distance, and finally, in the EU FP, the transport of 1500 of RBA to the facility at a 20 km distance was added. The overall results were similar to the baseline, with the EU FP scenario having the best performance in most impact categories. However, in the ozone depletion impact category, in which the EU FP alternative had significantly higher impacts than the EU BAU and EU BP, now has the lowest.

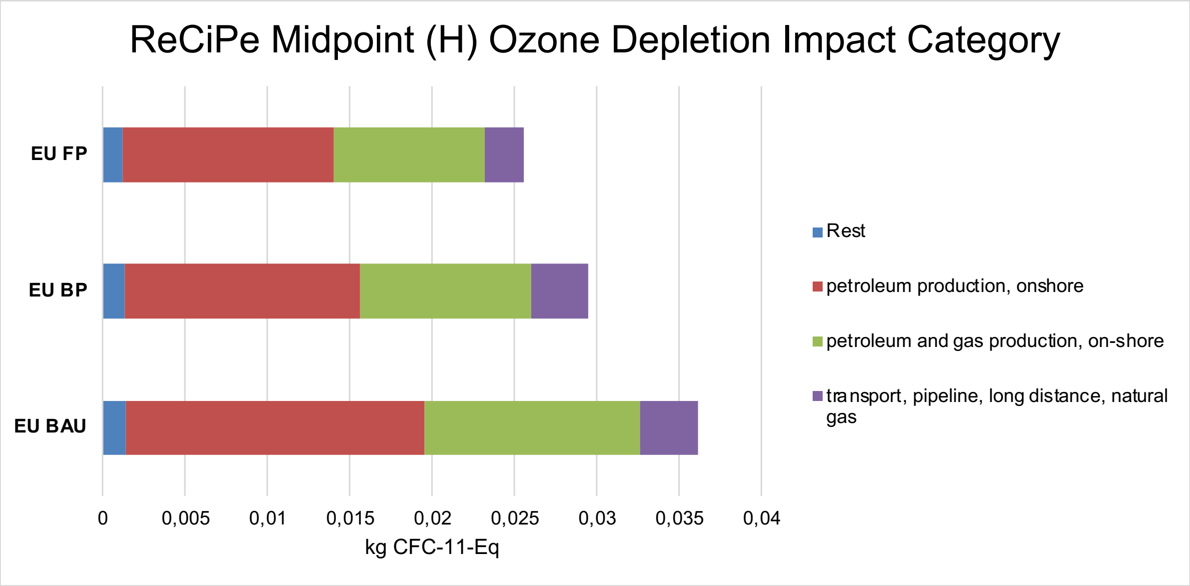


Figure 36. Sensitivity analysis results for the ozone depletion impact category

In addition, the difference in the climate change impact category is noticeable, with transport contributing to even higher absolute impacts of the EU BAU than the EU FP compared to the baseline results (Figure 37). No other considerable changes were identified in both the environmental and economic impacts.

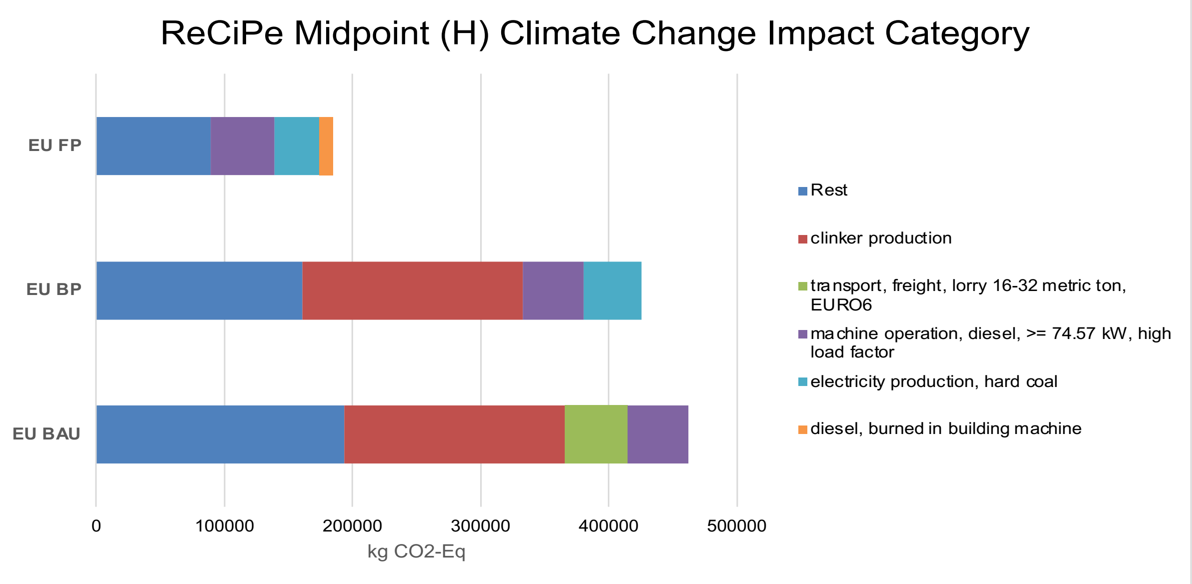


Figure 37. Sensitivity analysis results for the climate change impact category

(d) Crushed gravel production

The sensitivity analysis for the gravel production was carried out with two different approaches. The first approach was to reconsider the choice to expand the product systems and equalize to the highest output. Instead, the outflows were balanced based on the EU FP product system for the sensitivity analysis. The difference between the baseline approach is identified in the quantity of RBA, which amounts to 1500 tons in the EU FP scenario. Therefore, the initial 10500 tons produced by the EU BAU and EU BP product systems are adjusted to 1500 tons while the additional 9000 tons are expressed with a minus sign reflecting the avoided production process. Therefore, crushed gravel production is not necessary for the functional equivalence of the product systems and was omitted from the EU FP alternative.

The results were compared to the baseline analysis and the reduction of absolute impacts is evident across all product systems and impact categories. The most considerable reduction for the EU BAU and EU BP alternatives is observed in the fossil and ozone depletion categories at 46% and 48%. In the EU FP scenario, the absolute impacts are significantly reduced in multiple impact categories. In urban land occupation, natural land transformation and metal depletion the reductions ranged from 69-84%, compared to the baseline analysis results.

These changes also affect how the three alternatives compare relatively. Moreover, as seen in Figure 38, the EU FP scenario maintains the best performance in most impact categories, excluding ozone and fossil depletion. In the latter, the impacts are attributed to the on-site crushing activities for the production of recycled coarse aggregates. However, the relative difference between the EU FP and the other two alternatives is significantly higher compared to the baseline analysis. The highest contrast is identified in the urban land occupation category, in which the EU FP alternative has approximately 90% lower impact compared to the alternative with the largest indicator result.

Table 13. Adjusted amounts for the basket of functions as part of the sensitivity analysis

			Produced			Supplied			Total (tons)	
1	building	EU BAU	0	RCA		6840	NCA		6840	CA
			0	RFA		1728	NFA		1728	FA
			0	UF		432	Cement		432	Cement
			10500	RBA		-9000	RBA		1500	RBA
1	building	EU BP	0	RCA		6840	NCA		6840	CA
			0	RFA		1728	NFA		1728	FA
			0	UF		432	Cement		432	Cement
			10500	RBA		-9000	RBA		1500	RBA
1	building	EU FP	6840	RCA		0	NCA		6840	CA
			1728	RFA		0	NFA		1728	FA
			432	UF		0	Cement		432	Cement
			1500	RBA		0	RBA		1500	RBA

Table 14. Reduction of absolute impacts compared to baseline results for each alternative

Impact categories	EU BAU	EU BP	EU FP
Agricultural land occupation	30%	30%	58%
Climate change	30%	29%	17%
Fossil depletion	46%	46%	13%
Freshwater ecotoxicity	28%	28%	46%
Freshwater eutrophication	38%	37%	19%
Human toxicity	33%	33%	27%
Ionising radiation	31%	30%	43%
Marine ecotoxicity	29%	29%	45%
Marine eutrophication	32%	31%	34%
Metal depletion	24%	24%	69%
Natural land transformation	23%	22%	74%
Ozone depletion	48%	48%	14%
Particulate matter formation	24%	24%	40%
Photochemical oxidant formation	32%	31%	34%
Terrestrial acidification	26%	26%	35%
Terrestrial ecotoxicity	23%	23%	45%
Urban land occupation	8%	8%	86%
Water depletion	26%	26%	36%

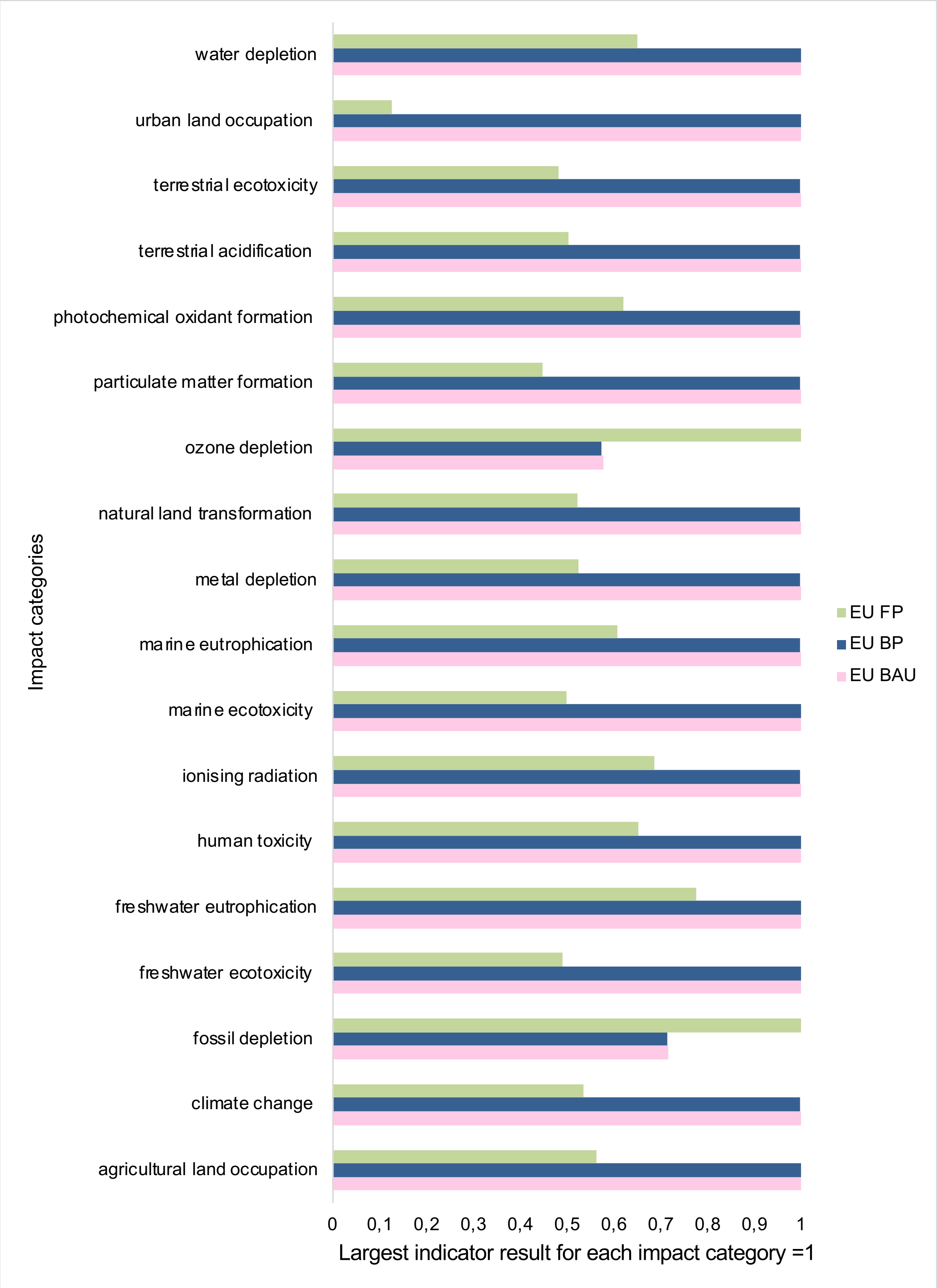


Figure 38. Sensitivity analysis results, relative to the largest alternative (=1)

The second approach entailed substituting the production process of crushed gravel with RBA. This is carried out based on the assumption that other demolition projects can supply RBA, as their on-site production constitutes a common practice in the Netherlands. The effects of this approach are reflected in the absolute impacts of the EU FP alternative. Aforementioned in the contribution analysis, crushed gravel production was the highest contributor in several categories, namely urban land occupation, natural land transformation, metal depletion, agricultural land occupation and freshwater ecotoxicity. As expected, the reduction of absolute impacts reaches up to 76% in urban land occupation, 59% in natural land transformation, 50% in metal depletion and between 3-27% in the rest impact categories. However, in most of the impact categories, there is an increase in terms of absolute impacts for the EU FP, which is attributed to the on-site crushing of aggregates, as seen in Table 15. Since the other two alternatives were not affected by the applied change, there is a decrease in the relative difference between the EU FP and the EU BAU and EU BP alternatives. However, the EU FP still presents lower environmental impacts in most of the impact categories and thus performs better than the EU BAU and EU BP alternatives.

Table 15. Sensitivity analysis (SA) results for the substitution of crushed gravel with RBA production in the EU FP scenario

Impact categories	**Unit**	**Baseline**			**SA**
		EU BAU	**EU BP**	**EU FP**	**EU FP**
Agricultural land occupation	square meter-year	7,86E+03	7,86E+03	7,43E+03	5,46E+03
Climate change	kg CO2-eq	3,94E+05	3,91E+05	1,80E+05	2,65E+05
Fossil depletion	kg oil-eq	8,19E+04	8,09E+04	7,05E+04	9,93E+04
Freshwater ecotoxicity	kg 1,4-DCB-eq	3,92E+03	3,91E+03	2,57E+03	2,48E+03
Freshwater eutrophication	kg P-eq	8,31E+01	8,31E+01	4,97E+01	7,16E+01
Human toxicity	kg 1,4-DCB-eq	7,04E+04	7,03E+04	4,25E+04	5,41E+04
Ionising radiation	kg U235-eq	2,78E+04	2,76E+04	2,32E+04	2,18E+04
Marine ecotoxicity	kg 1,4-DCB-eq	3,56E+03	3,55E+03	2,31E+03	2,28E+03
Marine eutrophication	kg N-eq	3,70E+02	3,66E+02	2,32E+02	2,72E+02
Metal depletion	kg Fe-eq	9,81E+03	9,75E+03	1,26E+04	6,29E+03
Natural land transformation	square meter	1,16E+02	1,15E+02	1,80E+02	7,35E+01
Ozone depletion	kg CFC-11-eq	2,38E-02	2,33E-02	2,47E-02	3,27E-02
Particulate matter formation	kg PM10-eq	4,31E+02	4,27E+02	2,44E+02	2,51E+02
Photochemical oxidant formation	kg NMVOC	1,09E+03	1,08E+03	7,02E+02	8,07E+02
Terrestrial acidification	kg SO2-eq	1,02E+03	1,01E+03	5,83E+02	6,47E+02
Terrestrial ecotoxicity	kg 1,4-DCB-eq	1,28E+01	1,27E+01	8,56E+00	7,72E+00
Urban land occupation	square meter-year	5,94E+03	5,93E+03	4,98E+03	1,17E+03
Water depletion	cubic meter	8,46E+02	8,46E+02	6,38E+02	7,00E+02

Note	
Decrease	⬜
Increase	🟩

5. Discussion

It is essential to interpret the results of this study in a critical manner, as they are based on assumptions specific to the adapted version of the ICEBERG case study. Moreover, It is crucial to acknowledge that the adaptation of the primary data was carried out based on estimations by field experts on how the ICEBERG circular solution would be ideally applied if the inherent limitations of the specific case study (e.g., technical specifications of the former detention center building, demand for concrete waste) were surpassed. Therefore, they do not reflect how the project was carried out in reality.

In addition, different assumptions on transportation distances and other reuse possibilities for the harvested components within local markets, which operate based on an established network of partners, might affect the results. Modeling choices, including the system expansion to accommodate the functional equivalence of the three alternatives, need to be considered. Specifically, the additional requirement for 9000 tons of RBA in the EU FP scenario, which was modeled with an Ecoinvent background process of crushed gravel production as a proxy, was proven crucial for the results. The process was the highest contributor to two out of three impact categories in which the EU FP performed worse than the other two alternatives. However, the overall better performance of the EU FP alternative was evident in environmental and economic impacts.

Furthermore, modeling of the LIBS equipment was simplified and limited to the supporting infrastructure, which includes a container and two conveyor belts. However, the percentage of the infrastructure attributed to the process was calculated based on the LIBS equipment's lifetime and not the supporting infrastructure's lifespan, leading to a possible overestimation of impacts. In addition, the possibility of reusing or recycling the container after its primary use in the project was not considered. Therefore, this approach not only results in not fully capturing the infrastructure's lifetime but also potentially attributing higher impacts (e.g., from steel production) to the aggregate processing with LIBS.

5.1 BIM-supported pre-demolition audits

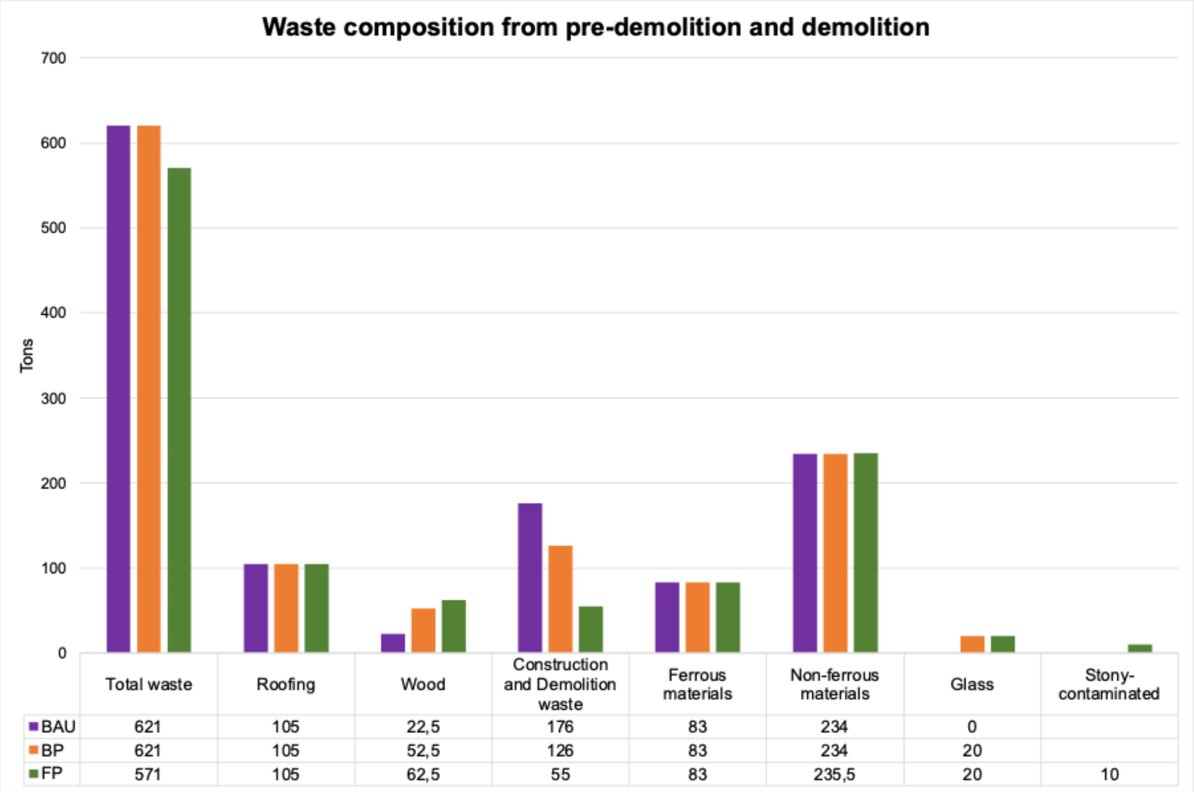
However, it is surprising that several interesting discussion points arise for parts of the system outside the concrete recycling process. Usually, the focus of similar research projects, as presented in the literature review, is concrete waste processing via different technological routes to increase environmental and financial benefits and embrace circularity. However, the opportunity to follow a case study entailing the demolition, waste processing, production of aggregates, and quality control with the consistent application of exemplary practices throughout the project has showcased the importance of stages before and after demolition.

Moreover, the BIM-aided-Smart Pre-Demolition tool utilized to perform the pre-demolition audit presented exciting insights. Since the equipment is a relatively simple portable editor with an installed power of 0.01 kW that was used for 8 hours, it does not deliver exciting results in the context of the LCA-LCC integrated framework analysis. In theory, it could have been omitted from the study without affecting the results or the research quality. In addition, it presents the challenge of considering process outputs that are not quantitative, such as the three-dimensional drawings, increased accuracy, the material inventory, the improved demolition decision-making plan, and the safety evaluation that result from its use in the pre-demolition audit.

From an economic standpoint, the insights offered by the BIM-aided-Smart Pre-Demolition audit can be estimated both in terms of cost reduction (< 2 euros/ m^2 of the built surface) as well as time savings. This argument is supported by the fact that it facilitates material traceability and prevents the discovery of additional asbestos or chromium sources that would take up to approximately three days to be treated. In addition, it provides a highly detailed inventory that surpasses the information level of a typical pre-demolition audit performed by experts manually. Therefore, it increases information and shapes how the demolition process is carried out, maximizes the recovery of materials, and the efficiency of waste management plans.

5.2 The importance of local markets

It is evident that selective demolition requires additional labour and machinery operation, as described in the EU FP scenario. However, it results in almost 50 tons or 10% less waste than the other two alternatives. As seen in Figure 38, in the EU FP scenario, the amount of CDW is 69% and 52% lower than in the EU BAU and EU BP scenarios. Moreover, higher amounts of wood for reuse and glass for recycling, that are usually crushed in the CDW, were collected. Overall, a smaller amount of waste is being produced and treated in respective facilities, and more components are saved and diverted to reuse.



	Total waste	Roofing	Wood	Construction and Demolition waste	Ferrous materials	Non-ferrous materials	Glass	Stony-contaminated
🟪 BAU	621	105	22,5	176	83	234	0	
🟧 BP	621	105	52,5	126	83	234	20	
🟩 FP	571	105	62,5	55	83	235,5	20	10

Figure 39. Waste composition in the three alternatives, excluding stony waste

This results in lower environmental impacts and additional proceeds from selling the materials and components to other stakeholders. The proceeds from reusing and recycling the harvested components in the EU FP scenario resulted in 53% and 20% additional profit compared to the EU BAU and EU BP alternatives. Adding to the contribution of the BIM-supported pre-demolition audit, since the demolition process is carried out in a faster and more detailed manner, the demolition company receives the material inventory in advance. Based on that information, it can coordinate with local networks and market stakeholders to allocate the harvested components for reuse in other projects or recycling. In that respect, almost all the materials derived from the pre-demolition and demolition (e.g., heaters, doors, mirrors, shelves, staircase handrails) would be reused in other projects. In most cases, transportation distance, would be within a 20 km radius of the demolition project (Figure 39). In the BAU scenario, these items, if harvested, would either be discarded or recycled. From an LCA perspective, the benefits of proximity cannot be quantified because external partners carried out the dismantling and transportation from the EOL building to the end destination. Thus, these impacts are not quantified. However, the financial benefits in the form of proceeds from their management are considerable from the project's commissioner's point of view, as presented in Section 4.3.61. Even though the direct environmental benefits cannot be quantified, it can be argued that smaller distances are beneficial, considering impacts and CO_2 emissions outside this project. In addition, longer distances might be economically unattractive for the external partners that are responsible for arriving at the demolition site, dismantling, and harvesting the components from the EOL, as well as road transport.

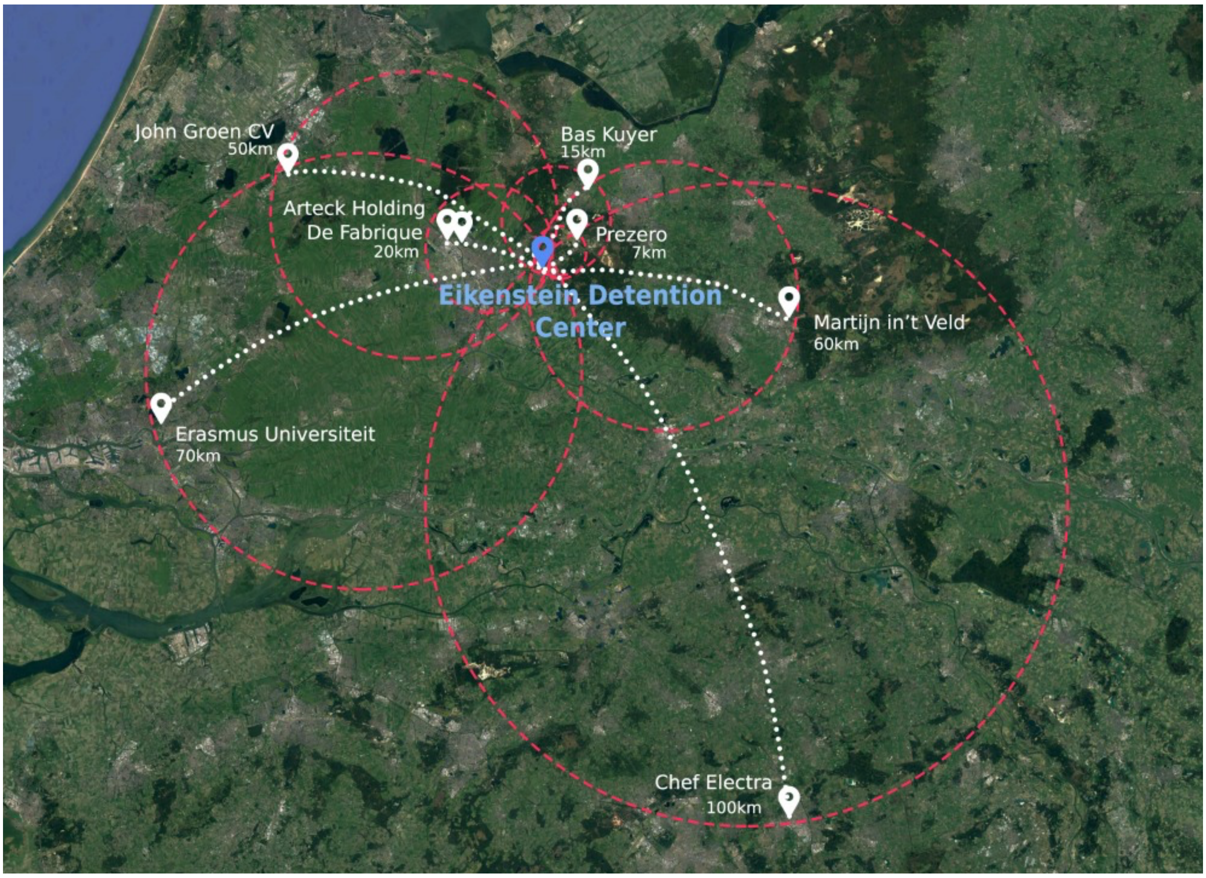


Figure 40. Map of destination businesses/ facilities that harvested components from the Eikenstein EOL building for reuse

It is worth to be noted that an additional reason that the reuse of components was possible is the existing established network of partnerships between the demolition company and relevant stakeholders. In other European countries, similar partnerships should be encouraged to improve the integration of harvested components from the demolition to new construction projects.

Moving towards this direction, the increased use of BIM to deal with existing stocks, as demonstrated by the use of BIM4DW in the case, and also to digitalize all relevant information for new buildings, can facilitate and support an online database with building information. This online database can be further developed to help establish networks and communication platforms for contractors, demolition companies, second-hand shops, architects, and other relevant stakeholders to coordinate projects and maximize the reuse and recycling of components from EOL buildings. However, distance should be a deciding factor for these partnerships to avoid shifting burdens from waste management to transport.

5.3 Assessing the quality of aggregates

It is established that the quality of aggregates is highly dependent on how EOL concrete waste is harvested from EOL buildings and the processing/recycling treatment to produce the recycled aggregates (Gebremariam et al., 2020b). In this context, the uptake of the ICEBERG circular solution package, from the demolition to the concrete waste processing, is an essential step toward the increased quality of aggregates. Moreover, the contribution of the C2CA advanced technologies in the production of coarse and fine aggregates, as well as ultrafine products that minimize the hotspot of cement production, reflects the future of concrete recycling.

However, it is important to acknowledge that the challenges of applying circular economy principles in the construction sector are not limited to the production of concrete aggregates but extend to their integration into the market, following a successful recycling process. So far, previous research can corroborate the high quality of aggregates by testing samples on a small scale. However, to support the uptake and enhance the market acceptance of recycled aggregates, the assurance of the quality of aggregates should be carried out on a large scale. LIBS offers the solution by characterizing the aggregates and providing information labels with all the necessary qualifications. This contribution of increasing the information level, endorsing the market acceptance of the recycled aggregates, and thus supporting the establishment of a market for secondary products cannot be fully captured and reflected in the LCA-LCC results.

6. Conclusion & Recommendations

The first objective of this project was to classify the concrete recycling and building demolition practices across Europe and how they affect the different options for EOL concrete recycling. The current average and best practices in demolition and EOL concrete management in Europe were explored through a literature review. The derived information was utilized to support the development of two scenarios: the EU BAU and EU BP. The EU BAU scenario includes a basic pre-demolition audit to identify hazardous materials, and it is performed in nations without pre-demolition audit laws. In this case, the demolition is non-selective, and the EOL concrete is crushed into RBA, as is frequently done in most European countries. In the EU BP scenario, selective demolition is used to identify hazardous materials and a limited number of recyclable materials. In countries like Germany, Finland, Spain, and the Netherlands, demolition is done selectively to recycle and reuse materials. The EOL concrete is crushed to RBA, similarly to the EU BAU. The ICEBERG case study for concrete in the Netherlands served as the base for the EU FP scenario. A thorough material inventory is created as part of the pre-demolition audit, assisted by BIM4DW. This guarantees a selective demolition plan geared to maximize component reuse and recycling. C2CA technology processes EOL concrete to create coarse, fine, and ultrafine aggregates. Quality control for the recycled coarse and fine aggregates is done using LIBS.

The second objective was to assess how the various recycling and demolition methods used by EU Member States compare in terms of their cost and environmental impacts. An additional task was to identify the possible economic and environmental advantages of implementing ICEBERG recycling and quality control technologies for concrete management on a European scale in conjunction with BIM-aided pre-demolition audit, selective demolition, and BIM. For this purpose, the environmental and economic performance of the three scenarios was quantified and compared within an integrated LCA-LCC study. Overall, the results of this study indicate that the combination of advanced BIM-supported pre-demolition audits, selective demolition, high-grade recycling with the C2CA, and quality assurance with LIBS as modelled within the EU FP alternative are promising for the integration of CE practices in the building sector. Furthermore, they showcase better performance from an environmental standpoint, with lower environmental impacts across most of the ReCiPe Midpoint (H) impact categories, reaching over 50% lower impacts in the climate change category compared to the EU BAU and EU BP alternatives. In addition, the economic performance also compares favourably. The EU FP alternative presents the lower total costs among the three alternatives, and the higher amount of proceeds surpasses the EU BAU and EU BP by 53% and 20%. However, it is imperative to acknowledge that the maximum overall difference in total costs is 5%.

Furthermore, the key areas where EU demolition and recycling processes need to be improved at each level, along with the obstacles that the EU must overcome to improve its recycling of concrete in the future, were researched. Different points of improvement were identified for each alternative. In terms of environmental impacts, cement production contributes significantly to all impact categories in the EU BAU and EU BP scenarios. Among the top contributors were machinery operation for crushing aggregates and diesel and electricity production processes, both of which are inputs for the machinery operation and the production of cement and aggregates. From an economic standpoint, the fees for processing the large amounts of produced waste, the supply of building materials and the machinery costs were the top contributors to the total costs for the EU BAU and EU BP alternatives. Even though the EU BP is differentiated from the EU BAU by a more detailed pre-demolition audit and selective demolition process, their performance is similar when comparing environmental and economic impacts. Therefore, these results show that when improved practices are only applied in certain stages and not consistently throughout the demolition project, they do not bear the anticipated results and can be considered half-measures. On the contrary, when a holistic approach is adopted, and pre-demolition audit and selective demolition are combined with high-grade recycling and efficient waste management of harvested components, as presented in the EU FP alternative, the environmental and economic benefits are considerable.

For the EU FP alternative, the production of crushed gravel is a prominent contributor in most impact categories, along with the RCA production within the combination of the C2CA and LIBS technologies. These impacts are associated with background electricity, diesel production, and machine operation processes. As discussed previously, these results are highly dependent on the modeling choices explained in the respective sections of this report and should be critically interpreted. In economic terms, the longer operating hours of machinery on-site, which are necessary for separating waste streams more effectively within selective demolition, result in machinery being the highest contributor. Labour is also a considerable contributor to the financial impacts, with more than double the man-hours required from demolition works on-site compared to the BAU scenario. This presents an interesting trade-off with the higher proceeds from selling the components and materials harvested from selective demolition for reuse and recycling.

Overall, it is evident that the potential uptake of the ICEBERG technological solution for demolition and concrete recycling can benefit the adoption of circular economy practices in the construction sector, as it entails environmental and financial benefits compared to current practices. Considering the anticipated demand for concrete aggregates for new construction and refurbishments, along with the urban mining potential in Europe that could address the waste generation and management issues as well as the resource depletion that results from well-established practices within the construction sector, the opportunity for scaling up the EU FP solutions is significant.

All in all, it is of high importance to acknowledge that part of the solutions, such as the pre-demolition audit to conduct a material inventory, selective demolition, and high-grade recycling, are not unknown in Europe but instead strongly recommended in the official protocols and regulations. However, most European countries are not adopting these recommended practices, despite their proven environmental and financial benefits. In that respect, no uniform framework on demolition and recycling practices is enforced, while the current regulations offer flexible definitions for selective demolition, recycling, and recovery without upholding high standards. Additionally, the market for secondary materials that result from high-grade recycling is underdeveloped in Europe, where networks of relevant stakeholders are non-existent. To account for these restraints, it is essential to uphold higher standards for selective demolition and recycling by updating current definitions and setting new objectives for the desired outcomes. Finally, it is imperative to set quality standards and standardize the quality control of aggregates before entering the market for secondary materials.

Reflecting on the results of the LCA-LCC study, it is important to acknowledge that the integrated method offers essential insights into the environmental and financial interrelation of the practices under examination and sheds light on the critical dynamics of environmental benefits and cost-efficiency. This combination of methods paves the way to explore problems in a non-mono-dimensional way. However, we fail to quantify essential benefits resulting from non-qualitative data by focusing only on costs and impacts. Moreover, as explained in the previous section, the LCA-LCC analysis cannot capture the potential benefits of the pre-demolition audit with the BIM4DW tool and the LIBS quality assurance method on a larger scale. The common outtake from these seemingly unrelated practices carried out in different life cycle stages of the EOL concrete is their contribution to increased levels of information that can shape the future of recycling on many levels.

Specifically, the pre-demolition audit can optimize the demolition process and ensure the maximization of recovered components by completing the inventory process with an outstanding level of detail that is digitalized and easily accessible. In addition, it contributes to the high-quality input of the EOL concrete fractions into the recycling process by shedding light on the exact material composition of every element within the building scheduled for demolition. Consequently, it offers indispensable information that presents benefits in different life stages of the EOL concrete, including demolition and waste management.

Similarly, the LIBS quality assurance tool follows the recycling of the EOL concrete, and it is the last step of the production stage. From this process, the aggregates are assessed, and a label with all the relevant information on their composition and quality becomes available. This information can assure the stakeholders within the market of secondary products about the quality of the aggregates they are purchasing and thus assist in overcoming the misconceptions about the lower quality of recycled aggregates. Accounting for the increased information levels in demolition and concrete recycling is challenging. Currently, evaluation tools cannot monetize information or capture its significance for the bigger purpose of establishing a circular economy in the construction sector. Based on the above, the necessity of improving our evaluation tools and combining multiple frameworks and methodologies is prominent in the efforts to enlarge our perspective on complex sustainability problems. In that respect, social-LCA and MFA are examples of methods that could complement LCA-LCC studies.

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