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Construction and Demolition Waste Management

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The goal of this thesis was to find potential ways of reducing the environmental impact of construction and demolition waste (CDW) throughout optimized recycling strategies and planned use and reuse of CDW throughout its entire lifecycle.

What was done to find potential ways to reduce the environmental impact of CDW?

The thesis found five ways to reduce the environmental impact of CDW in the various phases of construction: design for disassembly on the design phase, materials passports on the construction phase, high-grade products with high recycled content on the material production phase, extension of service life during the exploitation phase and selective demolition on the end-of-life phase. Their benefits and difficulties were discussed. The thesis can be used as an information package when planning for reducing the environmental impact of CDW.

Keywords	artificial intelligence, waste, sustainability, construction and demolition, circular economy, SDG

Contents

List of Abbreviations

AI	Artificial intelligence.
C&D	Construction and Demolition.
CDW	Construction and Demolition Waste.
EU	European Union.
WFD	Waste Framework Directive.
SDGs	Sustainable Development Goals.
EoW	End of Waste
ADR	Advanced Dry Recovery
DfD	Design for Disassembly.
UHPFRC	Ultra-high Performance Fiber Reinforced Concrete

1 Introduction

Construction and demolition waste (CDW) is the most considerable waste stream in the European Union nowadays, with constantly increasing amounts over time and high recovery rates. Although the high recovery rates might indicate that the construction field is highly circular, a thorough investigation of waste management practices makes it evident that CDW recovery largely relies on backfilling operations and low-grade recovery, such as using recycled aggregates in road sub-bases. [1.]

The amount of construction and demolition waste generated in 2016 was 374 million tonnes, making it the largest waste stream in the EU by weight. CDW has been defined a priority area in the EU Circular Economy Action Plan with the mandatory target for recovery set at 70% by 2020. However, construction and demolition waste is commonly down-cycled in reality. [1.]

The concept circular economy implies that raw materials are not taken out of their cycles but remain in the economical and production loop for as long as possible through their efficient and smart application. Through the reuse optimization or high-grade recycling, the value of the raw materials is supposed to be preserved. [2.] In the construction sector, this leads to buildings and construction elements that are designed to be flexible and easily adaptable to avoid unnecessary demolition. The recovery process of building materials or building elements should be quick and efficient, allowing high-quality materials to remain in a closed loop. Furthermore, broadening the scope of action would push waste management towards implementing the same approach into the other stages of the lifecycle of buildings. The series of actions made with circular economy in mind may affect the construction and demolition waste management profoundly.

To retain as much of the value of materials as possible is the main goal of the circular economy as stated in the European Economic Area Regulations 2016. This leads to a shift of priority focus from the quantity of recycling or reuse to the type of recycling, emphasizing the avoidance of down-cycling. The transition to a circular economy requires a series of actions that go far beyond waste management and improved recycling processes. All stages of the lifecycle of products have to be involved. [2.]

The policy objectives concerning construction and demolition waste handling stated in the European Union's legislation are [3]:

- The prevention of CDW generation – prevention is at the top of the waste hierarchy as described in the EU's Waste Framework Directive (WFD).
- The reduction of hazardous substances in CDW.
- The recovery of at least 70% of CDW generated by 2020.
- The reduction of greenhouse gas emissions from the management of CDW. Being also a broad environmental policy objective.

The quality and quantity of the construction waste generated in any specific project would vary depending on the circumstances and types of materials used in the project. The construction waste poses great danger to the environment. This has put the construction industry under pressure to consider suitable methods to protect the environment in all of its projects. Recycling of the CDW is one way to counter the risk the construction waste poses. Therefore, technology which helps to recycle these materials is of great importance. [3.]

2 Construction and Demolition Waste

Construction and demolition waste, by definition, consists of the debris generated during the construction, renovation and demolition of buildings, roads, and bridges.

Construction and demolition waste is generated throughout the whole lifecycle of the building. Waste is generated when a new building and new structures are built, and when existing buildings and civil engineering structures are renovated or demolished or deconstructed. Civil engineering structures include public works projects, such as streets and highways, bridges, utility plants, piers, and dams.

Construction and demolition materials often contain bulky, heavy materials such as

- concrete waste
- wood (from buildings)
- asphalt (from roads and roofing shingles)
- ferrous metals
- non-ferrous metals
- brick
- masonry
- glass
- plastics
- salvaged building components (doors, windows and plumbing fixtures)
- trees, stumps, earth and rock from clearing sites. [2.]

The revised Waste Framework Directive (WFD) clearly defines the waste hierarchy in waste management. According to it, waste prevention has the highest priority (figure 1). The WFD sets clear targets for the reduction of waste and requirements for waste management and recycling, including quantitative recovery targets for CDW. The end-of-waste concept is also introduced in the WFD. The concept includes defined criteria to establish when a waste stops to be one and becomes a secondary product or material. According to the WFD, “Member States shall take measures to promote selective demolition in order to enable removal and safe handling of hazardous substances and facilitate reuse and high-quality recycling by selective removal of materials, and to ensure the establishment of sorting systems for CDW at least for wood, mineral fractions (concrete, bricks, tiles and ceramics, stones), metal, glass, plastic and plaster". [4.]

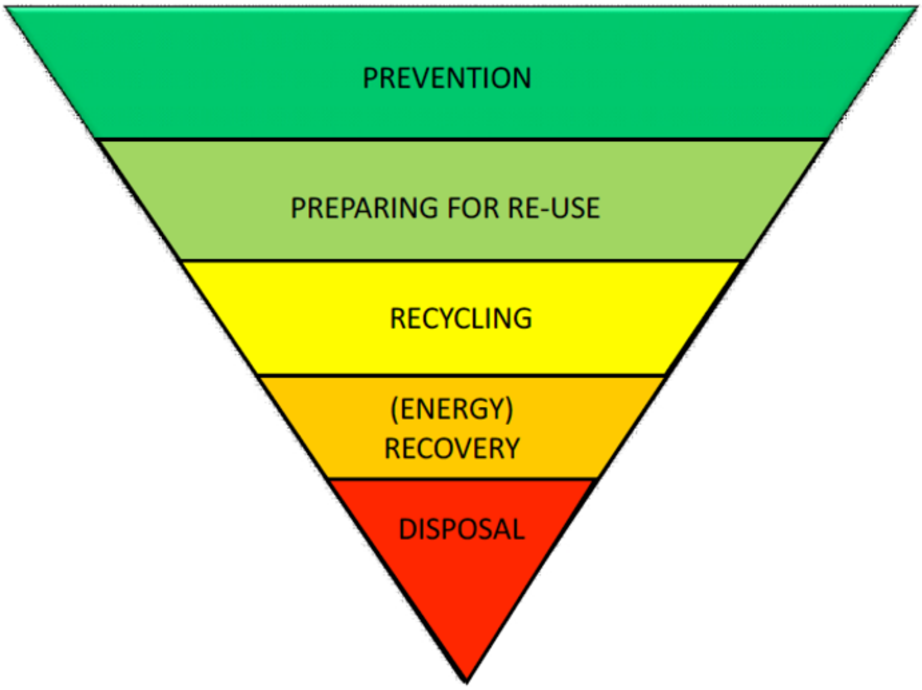

Figure 1. The waste hierarchy according to the Waste Framework Directive.

According to the revised WFD, the EU Member States are also encouraged to take proper measures to implement, among other things, the "production and marketing of products that are suitable for multiple use, that are technically durable and that are, after having become waste, suitable for proper and safe recovery and environmentally compatible disposal", which emphasizes the importance of the design and production phases for waste management. [4.]

In 2019, an implementation report on revised waste legislation supporting a circular economy was made available on the European Commission's website. This report describes the EU policies on products that influence the transition to a circular economy in selected priority areas, including construction. The document highlights that circularity and sustainability need to be assessed over the whole building lifecycle to optimize reductions of carbon emissions and material flows. Potential circularity in the construction sector is also discussed. [5.]

Table 1. List of actions mentioned in the Circular Economy Action Plan.

Action	Details
EU Construction and Demolition Waste Management Protocol (EC, 2016)	Any demolition, renovation or construction project has to be well planned and managed to reduce environmental and health hazards impacts while providing significant costs savings. The Protocol lists following actions to ensure the appropriate quality of C&D waste management process: improved waste identification, source separation and collection; improved waste logistics; improved waste processing; quality management process; congruent policy and framework conditions.
EU Waste Audit Guideline (EC, 2018)	The Guideline describes the waste audit process and elements to be included in it. The waste audit has to be organized by the owner of a building or infrastructure and should results in an inventory of materials and components arising from (future) demolition, deconstruction or refurbishment projects, and provide options for their management and recovery.
Building Sustainability Performance (EC 2019)	A tool for designing and constructing sustainable buildings. It is a voluntary reporting framework to improve the sustainability of buildings; it includes indicators reducing environmental impacts and for creating healthier and more comfortable spaces for occupants.

The resource efficiency is also one of the main priority focus areas among Sustainable Development Goals (SDGs). Sustainable Development Goals are collection of interlinked global goals designed to achieve more sustainable future. The three pillars mentioned in the SDGs concerning sustainable development are the economic, social and environmental pillars. Particularly relevant goals for a circular economy and resource efficiency are SDG 8.4 and SDG 12.2. [5.]

The SDG 8.4 aims at improving the global resource efficiency in consumption and production progressively, through 2030, and endeavouring to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programs on sustainable consumption and production, with developed countries taking the lead. The SDG 12.2, for its part, aims at achieving sustainable management and efficient use of natural resources by 2030.

Any demolition, renovation or construction project needs to be well planned and managed to reduce its environmental and health impacts while providing important cost benefits. According to the EU Construction and Demolition Waste Management Protocol there are following actions to increase confidence in the C&D waste management process and trust in the quality of construction and demolition recycled materials:

- Improved waste identification, source separation and collection
- Improved waste logistics
- Improved waste processing
- Better quality management
- Appropriate policy and framework conditions. [5.]

It is the responsibility of the owner of a building or infrastructure to organize the waste audit and control procedures. This, ideally, should result in an inventory of materials and components arising from (future) demolition, deconstruction or refurbishment projects, and provide options for their management and recovery. [5.]

3 Current Status of Management of Construction and Demolition Waste

3.1 Generated Amounts of Construction and Demolition Waste

The re-use strategy, recycling and other material recovery methods, including backfilling, are strongly pushed upon EU Member States. The revised WFD requires an increase to a minimum 70% of non-hazardous construction and demolition waste by 2020. It is worth mentioning that soil is not taken into account in the calculations. According to data from Eurostat, only the mineral waste recovery rate can be calculated with high precision level. Other available data on waste treatment does not present accurate information on waste origin. This informational gap leads to a considerable overestimation of the fraction of mineral waste recycling rates. [6.]

In 2016, the generation of CDW reached about 374 million tonnes (figure 2).

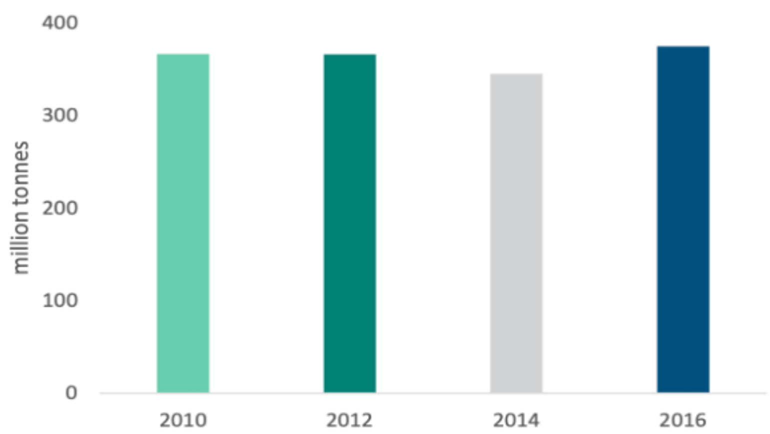

Figure 2. Generation of construction and demolition waste in the European Union, 2010-2016, million tonnes. [7.]

The amount of CDW generated is normally calculated as the sum of:

- ferrous metal wastes
- non-ferrous metal wastes
- mixed ferrous and non-ferrous metal waste
- glass wastes

- plastic wastes
- wood wastes
- mineral wastes from construction and demolition. [8.]

The mineral fraction of waste represents the biggest fraction of CDW generated. Figure 3 illustrates the fraction of mineral waste in various European countries. [8.]

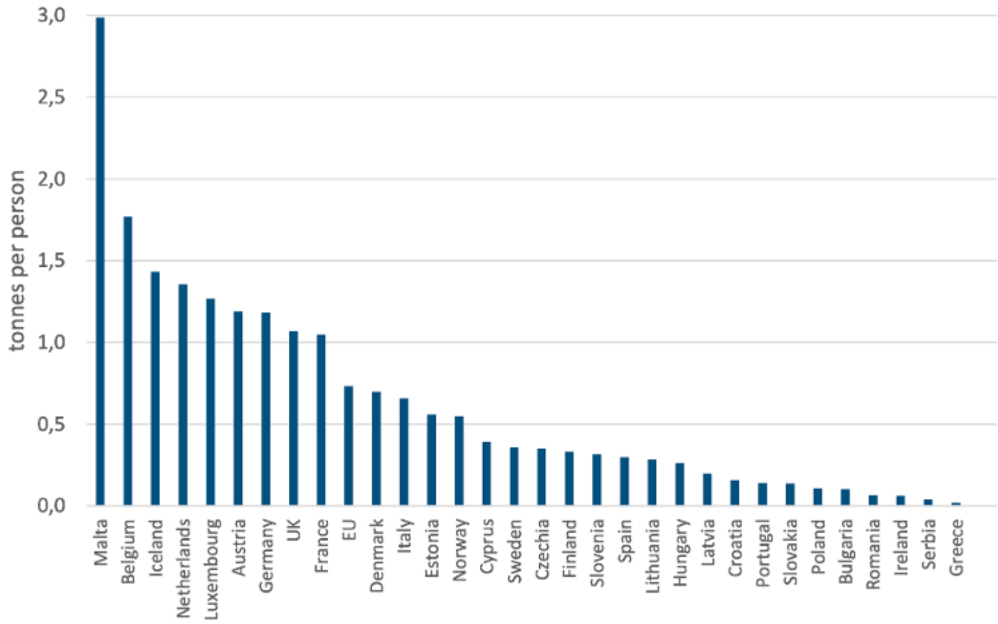

Figure 3. Generation of mineral waste from construction and demolition waste. [8]

The CDW generation has been relatively constant in the EU since 2010. Nonetheless, it is still one of the largest waste streams. Figure 3 illustrates the exact differences in CDW generation between countries and the significant gap between countries. [8.]

The reliability analysis of CDW statistics demonstrated that the CDW data in Europe has a quality score of 2.3 out of 5, ranging from 1.5 to 4.3. According to the study conducted, Austria, Czech Republic, Denmark, Germany, Netherlands, Poland, Portugal, Slovakia and Slovenia have on average good quality of CDW data. On the other hand, countries such as Bulgaria, Cyprus, Finland, Greece, Ireland, Latvia, Malta, Romania and Sweden have poor quality statistical data. However, uncertainties related to the CDW data in the best performing countries are still valid. For example, according to the Danish Environmental Protection Agency there is a high uncertainty about the amount of concrete waste generated in Denmark in 2015. The registered quantities were significantly smaller than the actual amounts of concrete waste generated. On the general and even superficial level, for most European countries, improvements in the quality of CDW data are necessary. [8.]

Deficiencies in data collection methodology lead to poor data quality. As long as countries are allowed to define the criteria for their data collection methods, a vast range of different methodologies lie behind Eurostat data. For example, the most common problems which tend to weaken the data quality are under coverage, double counting and misclassifications. The misclassification of soil waste is one of the most important and critical issues. In some countries, for example in Lithuania and Finland, excavated soils are wrongly included in the national estimated amounts of CDW. As a consequence, non-hazardous mineral waste from construction and demolition sector gets to be significantly overestimated along with its recovery rate. The poor quality of CDW data makes analysing CDW generation and management challenging and hinders comparison of data between countries. [8.]

3.2 Construction and Demolition Waste Treatment in the EU

According to Eurostat, the average recovery rate of CDW in EU was 89% in 2016. Eurostat defines the recovery rate as the amount of CDW that is destined for reuse, being recycled or will be directed to material recovery, including backfilling, divided by the amount CDW treated. The recovery rate of mineral waste of non-hazardous nature from construction and demolition in different countries in 2016 is illustrated in figure 4. Furthermore, Eurostat does not include data on reuse of construction materials or components in the data on the treatment of CDW. [9.]

The recovery rate of non-hazardous mineral waste from construction and demolition is generally high in the EU countries. Most countries already meet the WFD target for preparing for reuse, recycling or other material recovery, including backfilling operations. For instance, Luxembourg, Malta and the Netherlands have reported a 100% recovery rates in 2016. However, some uncertainties surrounding the reporting of CDW treatment by EU Member States are still valid. [9.]

Recycling CDW is often interpreted as using materials from demolished buildings and other structures in civil engineering projects. However, high internal recycling rate in the civil engineering sector leads to the sector being oversaturated with recycled aggregate. Nonetheless, secondary materials are randomly used in the building sector – in the Netherlands, secondary materials only represent 3–4% of all materials used in buildings. Therefore, high recycling rates cannot be considered as positive recycling indicator since CDW is mostly getting down-cycled. [9.]

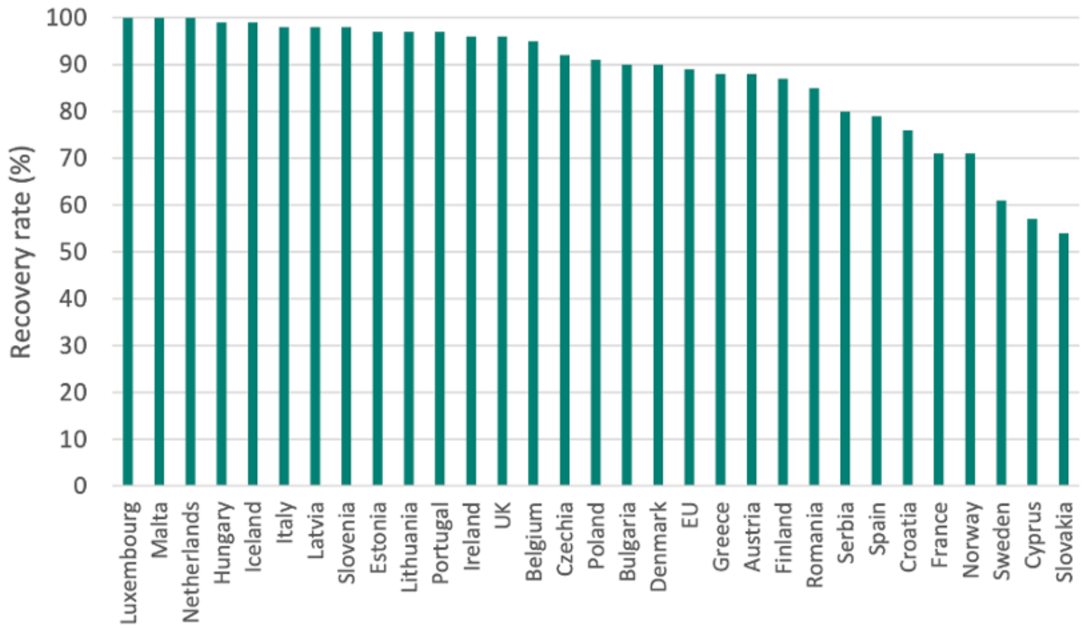

Figure 4. Recovery rate of non-hazardous mineral construction and demolition waste, 2016, %. [10]

In low-grade applications, in case of absence of availability of any alternative secondary materials, the use of materials from CDW is most likely encouraged. However, it is likely that the market of these more low-grade applications will decrease in the near future. The EU's "2050 zero land take" objective could restrict the low-grade applications and drop the market for road building materials. As a consequence, the market for recycled CDW materials has to be able to react and adapt promptly. For instance, by developing new technologies allowing the sage in higher-grade applications. [9.]

The waste hierarchy uses sustainability level to rank waste management options. Waste prevention is ranked as a top priority, followed by recycling, energy recovery and lastly disposal. [9.] The ratios of different treatment methods – recycling, backfilling, energy recovery, incineration without energy recovery, landfilling – of CDW mineral waste in 2016 are shown in figure 5.

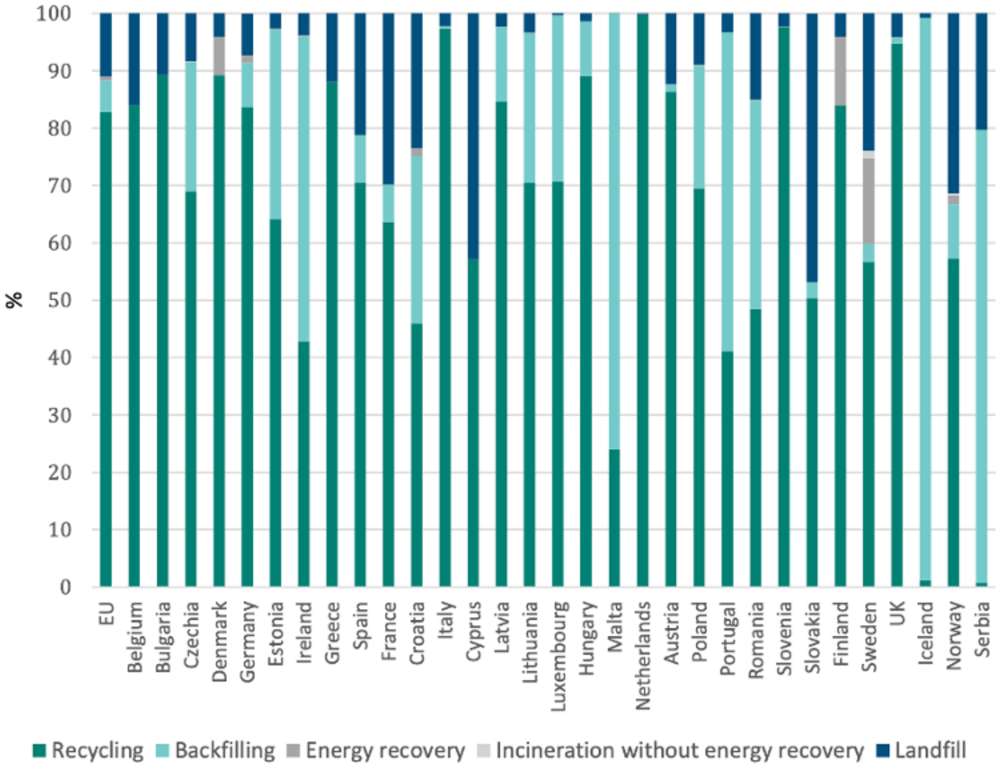

Figure 5. Treatment of mineral waste from construction and demolition, 2016, %. [11]

Nationwide criteria for CDW mainly concern the use of mineral waste from construction as aggregate. The End of Waste concept allows the amount of administrative work involved in handling permits for the use of CDW to be diminished. As a consequence, it may lead to quality increase of recycled materials. However, currently only Austria, Belgium, France, the Netherlands and the UK have developed and implemented such national criteria. A few other countries are working intensively towards the implementation of such criteria, too. Currently, the data available on the influence of the criteria on recycling rates is limited. In order to be able to analyse whether recycling rates have increased because of the regulations, more countries have to adapt these criteria. Presently, four out of the five countries with EoW criteria, with France being the exception, already have recycling rates above the EU's 70% target. [9.]

3.3 Backfilling in Reuse and Recycling of Construction and Demolition Waste

Backfilling is not specified in the EU's 2008 WFD, despite the fact that it is part of the CDW reuse and recycling target. Backfilling is described as "a reclamation activity in which suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping, where the waste is used as a replacement for non-waste materials." Waste used for backfilling must substitute non-waste products, be appropriate for the purposes mentioned above, and be restricted to the amount strictly required to achieve those purposes, according to the updated WFD. This new description could restrict the amount of material recorded as backfilled in the future. For example, the filling materials used in road edges, parking lots, and noise barriers are not always environmentally friendly or stable. [11.]

The WFD classifies backfilling as recovery, but the definition of recycling precludes its use for backfilling operations. Backfilling may be considered low-quality recovery; however, because backfilling CDW retains the use of its original materials and eliminates the need for additional natural resources, it is considered high-quality recovery. The amount of waste used for refilling and other material retrieval operations should be reported by the EU Member States separately from the amount of waste prepared for reuse or recycling. [11.]

4 Review of Available CDW Recycling Technologies

In this chapter, the technologies available nowadays for better waste management are discussed in more detail. The primary goal is to demonstrate the potential benefits of introducing circular action at various stages of the value chain using concrete examples. Not only the benefit of the recovery quantity will be taken into account, but also the type of recovery and the possibility to avoid the down-cycling. All actions are linked to the value chain, and the benefits cannot be allocated to a particular phase alone. [12.]

4.1 High-grade Products with High Recycling Content

High-grade products are materials or components used in structural elements of a building or infrastructure that have a long lifespan. It means products or components, such as products with sufficient strength, which withstand degradation during prevailing use. The lifetime of the end product is determined by the durability of the components. The use of high-quality products means that waste retains its value and contributes to the raw materials supply; the recycling of high-energy materials can result in significant CO_2 savings and the maintenance of waste in the material loop reduces waste generation for disposal. [12.]

Products made from recyclables must outperform those made from non-renewable resources, or at the very least meet high-performance criteria. When CDW is recycled, the mineral component is typically used in low-grade construction materials such as non-structural concrete applications like coarse aggregates for road bases, paving blocks, and embankment fills. The inherent value of CDW is greatly diminished in these cases because their potential structural properties are not utilized. By establishing a path that leads to their incorporation into high-quality products, the recycling system would make much better use of the CDW's inherent value, thereby preserving it. As a result, the use of CDW in high-quality products would avoid downcycling and adhere to the spirit of a circular economy. [12,13.]

Particularly important is high-grade concrete recycling, because it represents 42% of construction materials. Other construction waste, such as asphalt, chipboards, and some plastics, can be recycled, but in many cases the waste volumes involved are relatively small. In addition, some are country dependent, such as wood; or waste from construction activities, such as surplus materials, according to the Waste and Resources Action Program. [8.]

Concrete is made by combining fine and coarse aggregates, sand and gravel, cement, water, and additives. Coarse aggregate from demolition projects can be used to (partially) replace natural aggregates in high-quality concrete applications. The recovery of a high-quality stony fraction for recycling imposes requirements on all stages of the value chain, beginning with the planning of demolition activities to ensure that hazardous materials, for example, are removed prior to demolition, and ending with increasing end-user trust in the quality through a reliable tracing system. To ensure high-quality feedstock from demolition activities, tight quality control and new agreements between stakeholders in the value chain are required. Demolition waste streams of varying quality are produced if the demolition process is not carefully planned and supervised. The purity of the stony fraction generated during demolition, and thus the process chosen, is critical for the use of recycled aggregate in high-grade concrete products. [12.]

Several EU-funded projects, including C2CA, HISER, IRCOW, and VEEP, have developed and demonstrated advanced technologies for concrete recycling, including smart demolition to produce concrete waste with low contaminants and impurities level; new classification processes to obtain clean coarser aggregates; and sensor sorting to remove impurities of >6(mm). For example to be removed: wood, plastics, and gypsum from recycled aggregates. Thermal treatment for concentrating and purifying cement is applied along with laser-induced breakdown spectroscopy tools for ensuring the quality of input materials for concrete facilities. [12.]

The low cost of virgin materials and the manufacturing costs of demolition waste to secure high-quality material for recycling are the key impediments to recycling aggregates from construction waste in new concrete. Other barriers to recycling include variations in demolition waste quality, especially purity, if a strict quality control system is not in place. Concerns regarding the consistency of the recovered waste streams, as well as the possible existence of toxic materials such as asbestos, contribute to a lack of confidence or trust in them. [13.]

It is important to raise the market value of recycled concrete aggregates in order to make them competitive with natural aggregates. Some EU Member States, such as Belgium and the Netherlands, make the use of concrete aggregate an economically attractive option through government measures such as subsidies on virgin materials and landfilling waste taxes. National guidelines for the use of concrete waste in specific applications are also needed. Agreements and commitments between stakeholders in the supply chain are often needed for the use of waste in goods. [13.]

Concrete recycling may increase in the future as a result of sustainability concerns in the construction industry. In voluntary environmental rating systems for new or existing buildings, green materials with recycled content or environmental benefits are frequently given credits. Level(s) from the European Commission, Building Research Establishment Environmental Assessment Method (BREEAM) from the UK's BRE, and the US Green Building Council's Leadership in Energy and Environmental Design are examples of developed protocols. The protocols can be used by investors, designers, general contractors, and real estate operators to demonstrate a building's sustain-ability. [12.]

4.2 Advanced Dry Recovery

Fine material separation, or fines, defined as materials with a diameter of 0-1 mm, is critical for allowing high-grade recycling from concrete waste to new concrete. Fines produces more cement/mortar paste, which increases the amount of water needed to mix the 0-1 mm mixture and renders it sticky. In addition, the presence of sulphates and chlorides in the fines fraction of CDW complicates the processing. In the manufacturing of concrete aggregate, cement adhered to the surface of the coarse fraction needs special attention. [12.]

Throughout the Holistic Innovative Solutions for an Efficient Recycling project, initiated by European Union advanced dry recovery (ADR) technology for separating mortar from concrete was developed. The ADR is a low-cost mechanical process that can be used on wet materials without the need for prior drying or wet screening. [14.]

A schematic representation of the ADR process is shown in figure 6. The feed is a selective demolition concrete waste, which is broken into a material less than 12 mm in diameter. Autogenous fractionation is used to remove the loss of mortar from the surface of the aggregate. The first step is to break down the water bandage, formed by moisture from the surface of the fine particles which first remove fines under 1 mm in diameter and then coarse aggregate, 4-12 mm in diameter, and separate a thinner fraction with an impurity diameter of 1-4 mm, including wood, plastics and foams. [14.]

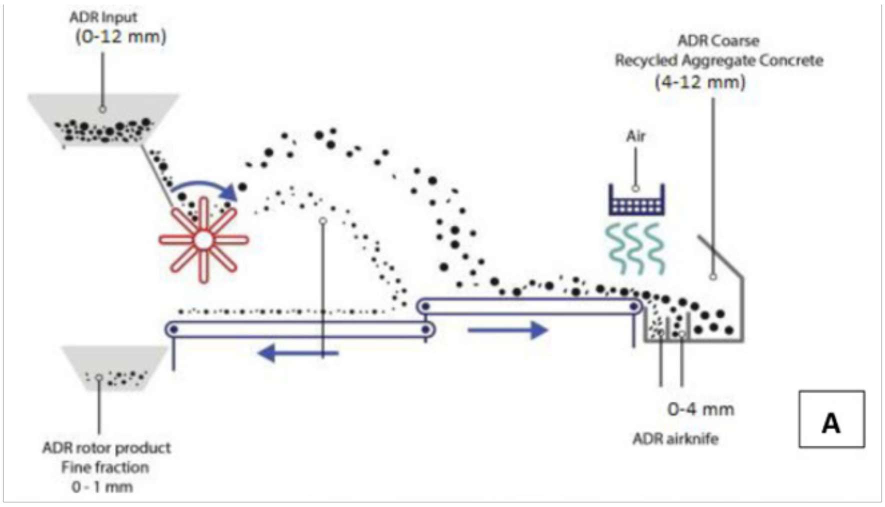

Figure 6. Working principle of advanced dry recovery. [14]

The ADR method was compared to the development of virgin aggregate in a lifecycle study, which revealed environmental benefits in 12 out of the 15 product environmental footprint (PEF) categories. On-site or nearby recycling provided the greatest environmental value. As a result, it is suggested that recycled aggregates be used locally. [14.]

The circular economy principles are supported by the recycling of CDW in high-grade goods with high recycled content, which keeps the value of the material in the loop and replaces virgin materials. In some applications, waste material can replace 20–30% of virgin material in concrete. If fines are removed from concrete waste, higher substitution, like multi-recycling cycles, can be achieved in high-grade applications. Because the coarse fraction of waste, with a diameter of more than 4 mm, accounts for nearly half of all concrete waste, it would be ideal if half of all concrete waste could be recycled in high-grade applications. [14.]

The key obstacles are fairly high production costs, and difficulty of quality assurance, both of which need traceability systems, lacking in many countries, for monitoring the origin of the waste stream. Due to the additional processing requirements, including a high content of recycled aggregate from CDW in high-grade products has no significant benefit for CO_2 emissions. The primary environmental benefit is the conservation of natural resources. [14.]

4.3 Design for Disassembly

The ability to recycle and reuse construction materials in the future is highly dependent on how structures are built today. Deconstruction, or design for disassembly (DfD), is a resource- and waste-efficient design strategy that considers a product's entire lifecycle. The key idea is to create items that are simple to disassemble into their component parts so that they can all be reused, reassembled, reconfigured, or recycled, thus enhancing their useful life. As used in the construction industry, design for disassembly allows individual building components to be reclaimed without causing damage to others or a loss of quality or value. Buildings built according to the DfD principles will serve as material banks, where construction materials are temporarily stored and then reused in the future, resulting in substantial resource savings and a significant reduction in a building's overall environmental lifecycle impacts, such as embodied energy storage, carbon emissions reduction, and pollution reduction. [15.]

The ease of disassembly is influenced by a variety of factors, including the building systems and technologies used – the quality of materials, reversible connection techniques, assembly sequences, accessibility, and so on – as well as the future availability of background information, the required time, and competence for (dis)assembly. Instead of nails, glues, welded solutions, or cement mortars, appropriate use of reversible technologies such as bolts, nuts, clip systems, screws, or even lime mortars are critical to facilitating and increasing potential component reuse. It is also necessary to ensure that the chosen materials are of high enough quality to withstand dismantling, transport, and reuse stages over time. [15.]

It is also important to have appropriate documents and knowledge about integrated construction systems on hand to help staff navigate potential disassembly. In an ideal world, the materials passports of a building are incorporated into a BIM model, making all knowledge required for deconstruction readily accessible at all times. Such documents should provide important details about a component's composition, history, and potential for reuse. [15; 16.]

Eight existing student housing modules at the Vrije Universiteit Brussel (Belgium) were renovated according to the DfD principles in the Circular Retrofit Lab (CRL). It was a pilot project within the Horizon2020 Buildings As Material Banks innovation project. Dismountable solutions for internal partitioning and the façade have been developed with the primary goal of converting student rooms into dissemination and office spaces that can later be transformed into other functional spaces without requiring new resources or generating additional CDW. [15.]

The goal for building partitioning was to study existing DfD wall solutions, evaluate their shortcomings, and then collaborate with industrial partners to create new solutions. In terms of material use, connection techniques, number of components, pre-fabrication, reuse capacity, and sub-layering, the result was a series of adaptable and reusable wall partitioning with differing properties. Then, rather than choosing a single tailored wall solution, a series of wall solutions that complement the various user flexibility needs in the building plan were chosen. [15.]

Three wall solutions were used in the Horizon2020 Buildings As Material Banks innovation project:

- Big prefabricated wood frame units with mineral wool filling and gypsum fibreboard panels
- A structural steel parts package made of 100% reusable steel profiles and interchangeable connectors and finished with demountable plywood
- Horizontal steel connectors with vertical wooden beams with tooth and groove. [15.]

Despite the fact that the solutions ere modelled using DfD concepts, the initial investment cost and environmental footprints were not always desirable, due to factors such as the construction materials used, the assembly process, and the type of finish. The results of the life cycle study were used in the decision-making process on which approach to implement. The pilot project highlighted the value of evaluating the long-term effects of DfD building solutions, including potential scenario planning. [15.]

The projected rate of change over the building's lifecycle was used to establish four wall turnover groups in the Horizon2020 Buildings As Material Banks innovation project. For example, in the Circular Retrofit Lab, which was one of the buildings developed with reversable building design concepts, certain walls, such as temporary display walls, are likely to be modified on a regular basis. Others, on the other hand, such as partition walls between living units, were less likely to alter over the building's lifespan. Wall solutions were then linked to these categories in collaboration with the design team and the wall manufacturer, including design requirements such as speed of assembly/disassembly, as well as acoustic and fire requirements. The reversible solutions were then compared to a standard drywall solution which is widely used in Belgium. Two different scenarios show that reversible solutions, including the reusable part steel kit, use large material streams, which lead to increased investment costs and higher initial environmental impacts. The potential for disassembly and reuse of this solution leads, however, to major environmental improvements compared to the baseline solution and if regular transformations are likely. If the proposal called for lower rates of change or none at all, the findings recommended choosing alternative DfD options to reduce lifecycle impacts. [15.]

Building design and components which support further dismantlement, selective sorting, reuse and reproduction can reduce the amount of CDW significantly. The high heterogeneity rate of the CDW currently leads to the reduction of large streams. Design for disassembly not only reduces the amount of products discarded as waste at the end of their useful lives, but it often allows for design for recycling, allowing non-recyclable construction materials to be quickly deconstructed and submitted for high-quality recycling. [15.]

Many cases of DfD design are still uncommon at the moment. Most of the construction projects in which DfD is prominently present were built as a result of an interdisciplinary collaboration between the design team and institutes of research, by the financial support of industrial partners or national and international financing initiatives. The general public is largely unaware of DfD – and even fewer are aware of its benefits. [15.]

The EU initiatives, such as the EU Action Plan for a Circular Economy and the Roadmap to a Resource Efficient Europe, are expected to aid in the promotion of building design practices like DfD that support resource efficiency and waste reduction. DfD building design, on the other hand, should always be accompanied by a lifecycle assessment or a lifecycle cost assessment that reflects the overall financial and environ-mental scenario. [4; 15.]

4.4 Material Passports Implementation During Construction Phase

In order to encourage resource efficiency, reduce CDW, and achieve the transition to a circular economy in the construction industry, accurate and standardized data on the material composition of the building stock and related products is needed. Materials passports, also known as construction passports or circularity passports, may provide the methods and data structure needed to obtain, handle, and provide this data. The passports contribute to bridging the current knowledge gap between relevant actors in the construction value chain closer. It is achieved by cataloguing building materials, components, and products and delivering the required data at the correct time. Their goal is to sustain or even increase the value of materials, goods, and components over time, as well as to promote reverse logistics and takeback, and to encourage reversible design. [17.]

Materials passports are described as follows in the EU Horizon2020 Buildings as Material Banks (BAMB) project, which ended in early 2019:

> Sets of data, including digital data, that describe the specified characteristics of materials and components in products and systems that provide value for immediate use, recovery, and reuse. They are a knowledge and education tool that asks questions about building materials that are frequently not addressed by other documents or certifications, particularly in relation to product circularity. The materials passports do not evaluate the data output or function as a data evaluator. Instead, they provide information that supports third-party tests and certifications, as well as allowing current assessments and certifications to be uploaded as documents to the passport.. [5.]

Various materials passports can consider various levels of complexity, ranging from the materials and components of products and systems that make up a building to the building stock for a specific area. Passports may describe a material's value for recovery, although they may also provide design-for-disassembly aspects and details of a particular product or system. For example, understanding how goods relate to a building is critical in explaining their reuse potential. [17.]

While materials passports have the potential to significantly contribute to a more circular construction market, there is still some confusion about their definition, financial implications, as well as the specifics needed. The added value must be demonstrated adequately to all stakeholders, and alignment with existing frameworks such as BIM is needed to scale the definition. Otherwise, in the historically conservative building industry, the introduction of materials passports would be daunting and sluggish.

The adoption and implementation of material passports has several benefits:

- When properly configured, they have the capacity to provide relevant information at the desired time while respecting users' and data suppliers' transparency expectations.
- The possibility of preserving and increasing over time the value of materials, goods and components, allowing circular design of product and material recovery, CDW eradication and downcycling. Better access to data would avoid expensive deconstruction mistakes and reduce the construction schedules.
- They enable better communication and cooperation between stakeholders in the construction value chain.
- Materials and goods' good visibility and traceability in the building supply chain is increased. [17.]

However, despite evident benefits, the following obstacles stand on the way of implementation of material passports:

- The legal issues of data ownership and control, as well as trade secret rights, arise when all valuable information is centralized.
- Costs associated with data collection and servicing are fairly high.
- Various players in the value chain have a high demand for details. This can be difficult in construction projects, which are often time constrained.
- Data collection methods need to be standardized throughout the entire life cycle of buildings. Current specifications, templates, and tools, such as BIM, must be compliant with materials passports. [17.]

In response to the BAMB project, EPEA GmbH established circularity passports. They comprise datasets containing the properties of building materials with the aim of creating value by mapping their recovery, reuse, and recycling capacity at various levels and making them accessible to appropriate parties at the appropriate time. Circularity passports are available to a wide variety of stakeholders, including product makers, building owners and consumers, dismantlers, urban miners and various sub-contractors. Different levels of knowledge allow for secure data exchange across the construction value chain. Over 300 materials passports for different items, parts, or materials were created during the BAMB project. [18.]

Where EPEA's circularity passports concentrate on building materials and components, Madaster considers the entire construction process. Their materials passports reveal the types of materials used in a structure, their quantities, details on material quality, location, and monetary and circular value. The Madaster framework is intended to serve as a public, digital catalogue of building materials. It makes data registration, organization, storage, and sharing easier while also considering privacy, protection, and continuity. Madaster is a self-contained website that provides unrestricted access to private entities, businesses, institutions, and scientific organizations. [18.]

Materials passports are data sets that describe specified circularity-related characteristics of building materials, goods, and systems. They have the ability to bridge the knowledge gap between actors involved in the construction value chain and provide accurate and standardized information on building stock material composition and material flows. They conserve material and product value over the lifecycle of the building in this way, promoting circular design, recovery and reuse activities, and reducing waste. Some measures have already been initiated, but in order for materials passports to become commonplace in the construction industry, their added value must be demonstrated to potential consumers, data providers, and other stakeholders. Convergence with existing systems, such as BIM, is also important. [19.]

4.5 Extension of Service Life of Construction

Enkvist and Klevnäs list the foregoing influential drivers for extending building lifespans:

- Upgrade and renovate existing structures rather than demolish them.
- Enhance servicing to prolong the life of essential (structural) elements.
- Create structures that are modular, fixable and versatile. [18.]

According to Enkvist and Klevnäs, extending the life of a building reduces CO_2 emissions significantly. By 2050, it is expected that the average lifespan will have increased from 64 to 91 years thanks to the use of circular models. In the long run, this will result in a 30% reduction in the need for new construction. Although extending the life of construction materials and buildings would result in less waste, the use of equipment, material requirements, and the production of renovation waste will all have an effect on the overall environmental impact. Durability design is the basis for long-term sustainability in new construction. Durable materials and rigorous design requirements reduce future cost of maintenance while increasing the value of a structure. Designing for increased longevity and ongoing maintenance reduces the total amount of waste produced over the life of a structure. Furthermore, building versatility lowers waste generation by extending the useful lives of buildings, for example by allowing a transition from commercial to residential use. The design for disassembly makes it easier to replace specific elements while the production of standardized components off-site allows higher standards of quality control to be applied and, therefore, reduces the risk of structural failure and long-term maintenance needs. [17; 18.]

The life time of existing buildings can be extended through maintenance, restoration and upgrading. Restoration consists of upgrading old buildings to comply with the existing legislation on energy efficiency, building directives and/or standards on comfort and use. Various rehabilitation degrees may be undertaken from maintaining all parts of the structure to retaining the envelope or the part of the building. [18.]

Future cost savings related to energy efficiency and historical value in residential buildings were assessed by Itard and Klunder given a lack of comfort in buildings designed under less stringent conditions, doubts about potential deterioration, and the need for specialized labour skills. Socioeconomic factors – the information base in the decision-making phase – are often linked to restrictions and drivers. Higher structural and quality requirements of new construction, as well as a lack of experience and confidence in contractors, are examples of common obstacles to residential building renovation. [18.]

The impact of two apartment buildings on the environment was compared in four scenarios by Itard and Klunder: routine building maintenance, renovation – insulation improvements, redesign – changing the floor plan to suit new demands, and reconstruction

– demolishing the old building and rebuilding/reconstruction with a new floor plan. This study arrived at one strong conclusion: reconstruction, rather than demolition and re-building, is a far more environmentally sustainable approach to obtain the same result. However, modification must be feasible, which necessitates a degree of versatility in the building design from the start. Reconstruction has the immediate benefit of reducing building waste. The analysis, on the other hand, establishes the following constraints:

- This operational energy consumption is equal to or less than it was before the reconstruction.
- The amount of materials used is smaller than for a new building.
- The design process is the same in both. [17]

Ultra-high performance fibre reinforced concrete (UHPFRC) is suitable for supporting reinforced concrete structures in critical zones exposed to abrasive environments or me-chanical stresses. On the basis of a bridge reconstruction in Slovenia, researchers eval-uated the lifecycle effect of various forms of UHPFRC and compared them to more con-ventional solutions. UHPFRCs have a low water/binder ratio, a high powder content, and optimized fibrous reinforcement, as well as low permeability, excellent longevity, and mechanical properties. To protect the full upper face of the bridge deck, footpath, and external faces of the curbs, a continuous UHPFRC overlay with no dry joints was applied to the bridge's upper surface during their renovation. The building process is both fast and long-lasting. The water-resistant properties of UHPFRC eliminate the need for a waterproofing membrane, allowing asphalt to be added to asphalt just seven days after the UHPFRC has been moist cured. When the higher longevity of the UHPFRC is taken into account – a longer service life and no need for multiple treatments – the lifecycle review indicates that rehabilitations with UHPFRC have a lower effect than conventional approaches. [16; 17; 18.]

The use of new construction materials is reduced by maintaining and extending the lifespan of buildings and other structures by smart maintenance, repairs, and renovation. The cumulative environmental effect of extending lifetimes is determined by the rehabil-itated structure's efficiency, as well as the duration of the extended lifespan. The envi-ronmental load produced by repair and restoration activities, as well as the use of re-sources such as water and energy over the structure's remaining lifespan, needs to be less than the load generated by demolition, new construction, and the resources used in new construction for the structure to have a positive effect. [17; 18.]

A new extended buildings' lifecycle phase has the potential to increase the viability of lifetime extension in a circular economy. Building recovery, for example, is more cost-effective if the structure is built to be readily upgradeable, versatile and flexible. The most important obstacles to improving the performance span of buildings are poor quality of existing structures due to the use of poor materials, improvements in community planning, scarcity of comfort according to current living standards, higher standards such as for energy efficiency, and outdated architectural design. [17.]

4.6 Reuse and Recycling of High-quality Waste Through Selective Demolition

Based on information from a pre-demolition audit, the ultimate goal of selective demolition is to extract high-quality material fractions for recycling or reuse. The aim of such an audit is to locate hazardous materials that must be removed prior to demolition and to determine whether or not they can be recycled. To ensure high-quality recovery, selective demolition is accompanied by material fraction processing. Selective demolition does not minimize overall waste output, but it does allow for the recovery of fractions for high-quality recycling. [16.]

Waste sorting conditions are inextricably related to selective demolition. There are legal criteria for sorting various waste fractions in Belgium, Denmark, Finland, and Sweden, for example. This ensures that the waste must be segregated at the demolition site, though mixed construction waste can be sorted at a special facility in each of the four countries. [16.]

Table 2. Legal requirements or recommendations for material-specific separation of CDW in Nordic countries. [18]

Materials	**Finland**	**Sweden**	**Denmark**
Brick/tiles	yes	yes	yes
Concrete	yes	yes	yes

Glass	yes	no	yes
Gypsum	yes	yes	yes
Insulation (stone wool)	no	yes	yes
Mixed stony fraction	no	no	yes
Mixed concrete and asphalt	no	no	yes
Paper	yes	yes	yes
Plastics	yes	yes	yes
Polyvinyl chloride (PVC)	yes	no	yes
Scrap metal	yes	yes	yes
Cardboard	no	no	yes
Tiles and ceramics	no	yes	yes
Wood	yes	yes	yes
Stone materials, e.g. granite	no	no	yes

There is a variety of boundary conditions that influence selective demolition, many of which are case specific. The most critical considerations are economic ones, which both promote and hinder the use of selective demolition. Selective demolition produces higher-value materials. A pure high-grade concrete waste fraction, for example, can be recovered instead of a mixed stony fraction. Furthermore, the sum of rejects that must be disposed of may be reduced. A more selective demolition procedure, on the other hand, is more expensive; it requires more labour and takes longer. This economic trade-off determines the selectivity of the demolition operation. Policy changes, such as taxes or legal restrictions such as landfill bans, will help to shift this economic trade-off. [18.]

Time availability, space, particularly in the urban environment, structural safety in the dismantling or the safety of the demolition work are all common factors that affect selective demolition. Complex building products or designs can make selective demolition more difficult or impossible in the future. For example, sandwich constructions with incorporated insulation materials are almost impossible to distinguish into various material categories. Buildings in the future, on the other hand, could be designed to be disassembled quickly. [18.]

Factors facilitating the implementation of selective demolition:

- Many EU Member States have made selective demolition mandatory. Construction decontamination is required – hazardous materials must be removed.
- Pure CDW fractions have a higher value. Following selective demolition, treatment costs are reduced. Environmental success can accompany financial success if a market for material recovery can be identified and connected prior to demolition.
- The use of efficient selective dismantling allows for the separation of undesirable fractions from recyclable CDW and improves quality.
- Link to BIM data in new construction. Disassembly design.
- Material recognition methods have been improved. For demolition work, robots are used. For high-grade material fractions, new recycling technologies are being created.
- Universities provide circular economy study programs at various educational stages. [18.]

On the other hand, there are factors preventing or slowing down the implementation of selective demolition:

- In certain EU member states, there is no demand for selective demolition. The safety standards for selective demolition are higher.
- Selective demolition lengthens the demolition process and necessitates additional manpower.
- Harmful substances may be present. Poor details on the origin and condition of waste materials due to a lack of traceability.
- Landfill and virgin materials are also inexpensive. Noise pollution and dust are created in the neighbourhood, and there is a shortage of land.
- The cost of selective demolition and material separation increases as buildings become more complex. Some building materials, such as sandwich elements, cannot be economically differentiated. Old buildings are not designed to be quickly deconstructed (from structure to components) or disassembled (from components to materials).
- In older buildings, material recognition is not yet possible.
- Numerous stakeholders are engaged in the value chain; cooperation is a struggle. [18.]

The use of old bricks rather than new ones in building facades adds architectural value and has gained traction in Denmark. The mortar is removed from old buildings and the bricks are cautiously removed, collected, and polished. The labour-intensive demolition and cleaning processes boost the cost of the bricks as opposed to new ones. Functionally, the renovated bricks meet the specifications for reuse, and a cleantech company called Gamle Mursten has branded and patented them. A circular economy model for selling recycled bricks has been created with the support of the Danish Environmental Protection Agency. [18.]

In Denmark, a demand for old brick has been generated, with a capacity of 30 million bricks per year, or about 10% of total brick manufacturing. Nevertheless, some challenges still exist for example, only limited batches of bricks may be available from a demolished house, there may be considerable variance in the quality of the bricks, or there may be a need for closer coordination amongst demolition contractors and recyclers.

In a lifecycle study, the environmental impacts of reusing bricks and recycling crushed bricks were contrasted. The findings show that reuse significantly reduces both environmental and economic impacts. When bricks are reused, both energy and new materials are saved. Brick reuse saves a large amount of CO_2, with an approximate reduction in greenhouse gas emissions of around 0.5 kg CO_2-eq per brick. [19.]

Numerous different countries use recycled bricks as well. In Belgium, for example, fired full face bricks bricked with a lime base or other soft mortar, which were commonly used prior to the 1950s, are often reused because they are easy to clean and have a high value. The majority of the time, reclaimed bricks are used for decorative purposes and are not part of the load-bearing structure. [19.]

The Tracimat quality control framework was created in Flanders, Belgium, and it includes the following features:

- List of items to be demolished.
- Flow control and surveillance.
- Classification scheme for selective demolition and demolition materials to be approved as "low environmental risk material". [19.]

Tracimat's function is to serve as a traceability system that ensures the quality of the preferential demolition process and the waste streams created. Tracimat certification indicates that demolition waste has been selectively obtained and traced, assuring the recycling company of the integrity of the recycled demolition waste – guaranteeing its origin and quality as contaminants-free. [19.]

Tracimat concentrates nowadays on decontamination, or the elimination of dangerous waste, since a clear stony non-contaminated waste stream fraction with a reduced environmental risk has obviously superior upcycling value. The certificate increases consumer trust in the material's efficiency, resulting in a stronger and more common demand for recycled goods. [19.]

At the time of approval, the Flemish environmental authorities require crushing companies to differentiate between products with a low and high environmental risk, with the latter requiring more rigorous processing and quality evaluation. This risk profile is determined by the demolition phase that preceded it. The processor will recognize and process demolition waste as low environmental risk material if the CDW is accompanied by a Tracimat certificate. Auditor preparation is an integral aspect of the Tracimat traceability scheme. [19.]

In the EU HISER project, the Tracimat method was compared to standard practices. The project established that in some environmental categories, a Tracimat sponsored case results in a significant reduction of 7–14% in the potential effects. Acidification had a 14% effect, terrestrial eutrophication had a 10% impact, aquatic eutrophication had a 7% impact, and photochemical ozone depletion had a 7% impact, all based on product environmental footprint estimates. [19.]

Selective demolition does not always result in higher recycling rates, but it is a requirement for the recovery of high-quality building fractions and following high-grade recycling, preventing downcycling. The environmental benefits of selective demolition are highly case-dependent, depending on the fraction recovery capacity, for example. The amount of CO_2 saved is determined by the amount of processing and equipment needed, as well as the distances between recycling facilities. [20.]

In life-cycle studies, the value of sustainable natural resource usage is not thoroughly discussed. A new resource depletion impact assessment is focused on the extraction and use of finite elements, as well as the use of fossil fuels. According to EN 15804, the current abiotic depletion potential (ADP) measure in lifecycle studies focuses on fossil fuel usage or the exploitation of scarce elements, but may not sufficiently account for the conservation of other natural resources. [19; 20.]

The most significant impediments to selective demolition are economics – the valuation of segregated fractions and immediate needs, such as distance to recycling facilities for separated or processed materials, as well as the additional time required for targeted demolition. In addition, a lack of clarification about the consistency of the separated fractions makes selective demolition difficult and has an effect on the value. Furthermore, the chance of loss during dismantling reduces the product's worth. [20.]

Buildings may be designed to be disassembled quickly in the future. That being said, the existing use of advanced components, which combine many materials to provide energy efficiency, can make selective demolition difficult. Additionally, the use of BIM resources to provide knowledge on accessible materials flows offers opportunities for environmental and economic benefits to be maximized. [19.]

5 Conclusion

Multiple shortfalls still obstruct the transition to a circular economy in the built environment, many of which are related to past or current construction practices. To create a truly circular economy, additional incremental steps must be taken, such as focusing on the entire lifecycle of building materials in a way that conserves energy and closes the cycle.

Elevated circularity concerns throughout a building's lifecycle have the ability to help meet waste policy goals, as seen in the cases and examples examined in the thesis. Due to increased production requirements, such as electricity, or effects on the environment from necessary maintenance and recovery, the advantages are often highly context sensitive. The overall environmental effect of the circular economy solutions is determined by the systems' whole, or several, lifecycles, which may last decades.

In the long run, all the cases discussed in the thesis resulted in better CDW management. The use of reuse solutions reduced material consumption, and lower-carbon alternatives, particularly during the design and construction phases, would provide significant environmental benefits in both waste prevention and less waste produced. Furthermore, partial replacement of cement with other raw materials in recycling concepts could result in substantial CO_2 savings in the future.

All cases discussed in this thesis had some major challenges, mostly financial, but also quality problems and setbacks in disseminating observable results. Production methods that use waste as an input material can only succeed if the manufacturing costs are lower than those of virgin resources, and if consumer acceptance is guaranteed. In regions with limited mineral resources, a scarcity of primary resources could change the market conditions in the future. Policy interventions, such as quotas on virgin products, can have a significant impact on market dynamics. Green public procurement, landfill fees, end-of-waste criteria, and extended product liability are examples of other policy initiatives. Extended product responsibility, on the other hand, may not always be suitable for items that stay in a structure for the duration of its existence.

Aside from economic aspects, the quality of construction goods and materials is critical to the adoption of circular economy strategies. The lack of recorded details about the source of waste and lack of data about the composition of historical construction materials may raise questions about their consistency. The use of traceability systems for recyclable materials and sustainable goods has been described in many cases discussed in the thesis as critical for building trust within value chain stakeholders. The value of building information modelling (BIM) as a tool for material inventories and traceability was also emphasised in several of the cases discussed, as it carries information on construction products over their entire lifecycle, from conception to demolition. Building materials passports can also be made with details on repairs, reuse, and recycling. Pre-demolition audits using traceability methods, BIM, and materials passports can all help to distinguish reusable and recyclable building items. Policies may help to encourage these systems and technologies, especially in government-funded construction projects, such as green procurement contracts.

The lack of concrete circular economy gains in the construction sector, which can take decades, may deter stakeholders from implementing new material or product management approaches. All parties in the supply chain must be on board for circular economy frameworks to be implemented successfully. Moreover, producers face difficulties in retaining liability for goods that will be in use for several years. Consensual sustainable building strategies would most likely affect the adoption of new methods and concepts in the future, with implications for the volume of waste produced and waste treatment.

Standardization is critical in evaluating the performance of the recycled share of a product in products that replace virgin materials, as well as in the development of building materials. Standardization is frequently used as the foundation for permits used in commerce and industry. Over-specification is used in some specifications to ensure consistency, but it can also result in an increase in the use of raw materials. As specifications are updated, consideration should be given upon whether construction performance experience and the implementation of tools to monitor material quality, such as non-destructive performance methodologies, may facilitate improvements in material requirements.

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