Concrete as a Palimpsest

The Value in the Deconstruction and Reuse of Structural Concrete

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Abstract

This paper concerns the deconstruction of buildings as an alternative for demolition. Deconstruction has environmental, social and economic benefits since it allows the reuse of existing materials. Reuse within the construction industry has the potential to reduce waste streams while decreasing the demand for excavation of natural resources. The paper proposes a system for reusing in-situ concrete in new construction. For that, it provides a first exploration of the various aspects pertaining to such a system. As the preliminary findings show that the phase of cutting is technically viable, an estimation of possible energy saving is made. The analysis compares energy consumption of cutting methods for reuse in comparison with common recycling methods. This estimation tests whether the proposed method is favorable in terms of energy. The conclusion is that further research and testing are required in order to determine the feasibility of the system as a whole and the conditions and effects if coming into practice. Furthermore, a standard method for reuse must be developed in order to introduce the system to the market.

Keywords: *deconstruction, concrete deconstruction, concrete reuse, concrete recycling*

I. Introduction

The construction sector has a significant role within the transition to a circular economy. An economy that values natural resources and acknowledges Earth's finite raw materials. Practices of deconstruction of buildings enable a more circular behaviour in regard to materials and energy conservation through reuse. While the current challenges are discussed in a general manner, one specific solution will be further explored in regard to concrete. It is of high importance to expand and develop activities of deconstruction and reuse to include concrete, as it is the most dominant material in our built environment (Preston & Lehne, 2018), with a production of some 33 billion tons per year (*Strategic Business Plan Iso/Tc 071*, 2016).

This paper marks the end of a thematic research, which aims to support an architectural design proposal as part of a Graduation studio in Architecture. The design proposal is for the redevelopment of a site in Brussels owned by the municipality. For the purpose of the material selection phase, the option to reuse existing structural concrete from a nearby site, the World Trade Centre (WTC) towers, is specifically examined. The towers are currently being deconstructed to make place for a new project called ZIN. Therefore, the paper focuses on the Belgian context at large, with the intention to formulate a generic system, while using the specific locations of a design proposal in Brussels, Belgium.

In Belgium, a high percentage of concrete is recycled after a building has been demolished or deconstructed (European Environment Agency, 2020). However, an opportunity lies in reusing the existing material instead of using it to produce new material. Whilst researching the subject, there appears to be a gap in research or practice concerning the reuse of in-situ concrete. This paper offers an exploration of the broad conditions in order to promote deconstruction and reuse of concrete. Focusing on the environmental aspect within our economic system, the main question driving my research is: ***what actions will be required to bring about a transition from conventional demolition***

to deconstruction? More specifically, this paper will ask: ***How does deconstruction relate to our current economic system? What technical and managerial developments could support such a transition?*** And ***How can principles of deconstruction and reuse be applied to concrete?***

To address these questions, this paper will provide a review of the relevant literature, as well as deconstruction projects, which will act as case studies providing more practical insight. To examine key issues more pointedly, in regard to the latter question, a series of personal interviews with professionals and academics is conducted to gain insight. Furthermore, a quantitative analysis of the energy required for the process of concrete cutting is presented.

The paper argues that the practice of deconstruction and reuse should be extended to include concrete as part of the transition towards circular and sustainable development of the built environment. In ***Chapter two*** the term deconstruction is defined, in contrast to demolition, with its environmental, economic and social benefits. In ***chapter three*** the barriers and challenges transitioning to deconstruction and reuse are mentioned, in light of the current economic system. ***Chapter four*** provides a brief description of current practices with concrete, and based on these, an alternative method is offered to allow the deconstruction and reuse of concrete. The viability of the method is examined from various relevant aspects and finally, a quantitative energy analysis is executed to test viability in terms of energy consumption.

II. Deconstruction as an Alternative for Demolition

2.1 Definitions

In the most general sense, demolition is the removal of buildings. The term demolition often refers to "*the complete elimination of all parts of a building*", which marks its end of life (Thomsen et al., 2011). While techniques and procedures are slowly changing, the term conventional demolition refers to the removal of a building by heavy machinery. The use of machinery varies from hand power operated tools to wrecking equipment and even explosives in some cases (Dardis, 2012). In her book *Bulldozer: Demolition and Clearance of the Postwar Landscape* (2016), the historian Francesca Russello Ammon offers an explanation as to how these became common methods of demolition. Ammon explains that conventional demolition has originated from practices of removal and clearance from partly damaged buildings after the second world war. The accelerated development of heavy machinery during the war made its way to the construction and demolition industry and remained common practice until today.

A typical demolition procedure involves identification of hazardous materials, which must be treated carefully. Subsequently, the building is knocked down, the waste is crushed into pieces, and traditionally transported to a landfill (Pilloni, 2014). In recent years in Europe, a significant amount of the waste has been recycled. Construction and Demolition (C&D) waste in landfill has a significant impact on the environment. Among the environmental issues are: reduction of the fertility of the soil; the hazardous effects that non-inert materials such as lead, tar, asbestos or paint might have over time and the leachate from unlined landfills, which poses a potential risk to surface water and groundwater (Yuan et al., 2011). However, while these could be addressed more locally, a major issue is our finite natural resources on Earth, which requires more holistic solutions. Luckily, there is a growing awareness that a drastic shift in our approach towards waste management and use of natural resources is required. One widely accepted approach is the circular economy, which can be understood as "*an economic model that gradually decouples economic activity from the consumption of finite resources and aims to design waste out of the system*" (Kanters, 2018, p.2).

Deconstruction, by contrast to demolition, is 'unbuilding'. The term deconstruction is widely accepted for "*the systematic and careful disassembly of buildings to recover valuable materials. In a sense it can be referred to as 'construction in reverse'*" (Munroe et al., 2006, p. 377). By practicing deconstruction the separation and recovery of components and materials becomes possible and allows reuse instead of use of new material. Researchers show that deconstruction can divert up to 90% of C&D waste from landfill by salvaging materials to be later reused or recycled (Munroe et al., 2006).

Recycling can be then divided into 'downcycling' and 'upcycling'. Downcycling refers to "*reprocessing a material into a lesser economic value and lower potential for future reuse or recycling*", whereas upcycling is when the end product "*results in a product of increased quality, greater potential for reuse/or higher economic value*" (Munroe et al., 2006)). A Dutch report states that currently most recycling has a low value recovery (backfilled for example), while high quality recycling remains below 3% (Provincie Limburg, 2020).

Thomsen et al. (2011) offer a view that considers the "*large amount of embedded natural, social and financial capital in the built environment*" (p.327) and therefore the understanding that building survival and demolition play a large role in sustainability and resource management. This approach perceives the existing built environment as a significant resource. As 38% of the total energy demand in Europe is consumed by the construction industry, this energy can be seen as a significant part of the embodied energy in our built environment (Durmisevic et al., 2017). Taking that as a departure point means that reuse and recycling of building materials partly preserves the embodied energy (Munroe et al., 2006) and decreases the demand for energy needed process raw materials.

A critical part of the transition towards circularity is a changed perception of waste: from useless materials to valuable resources. One implication of this view is that construction and deconstruction are seen as part of the same industrial cycle (Thomsen et al., 2011). In other words, in a closed loop the 'waste' of one sector can be a valuable resource for another. It is important to note that practices of demolition are changing, and in Europe, most demolition contractors are practicing some level of salvage (Couto & Couto, 2010). A selective salvage is quite popular and refers to cherry-picked removal of valuable items prior to demolition, including scarce materials or components. Furthermore, the amount of C&D waste being recycled is in constant growth and requires the systematic separation of different materials.

2.2 Stakeholders Involvement

"No discipline can claim demolition to be its own" (Thomsen et al., 2011, p. 332)

Demolition has a societal nature, and therefore related challenges are multi-faceted rather than merely technical. For this reason, demolition cannot be controlled by one profession, but relies on the involvement of actors from various disciplines (Thomsen, 2011). Accordingly, a change in demolition practices will require a transdisciplinary research, as well as the coordination and dialogue among the actors. This section provides an overview of the different actors. First, the actors are roughly divided into four categories (Het Utrecht Sustainability Institute. 2016). Secondly, the actors are positioned along the building life span according to their role throughout the construction and end-of-life cycle (fig. 2.1):

1. Professionals: architects, engineers, contractors and demolition companies which add or remove building materials from the building stock
2. Public policy makers: municipality, government and research and educational organizations who influence codes, norms and policy
3. Stakeholders/real estate developers: governments, housing corporation, real estate developers, managers, property owners and the client
4. Others: waste processing companies, distributors and material producers involved in the waste management, raw material and building materials chains.

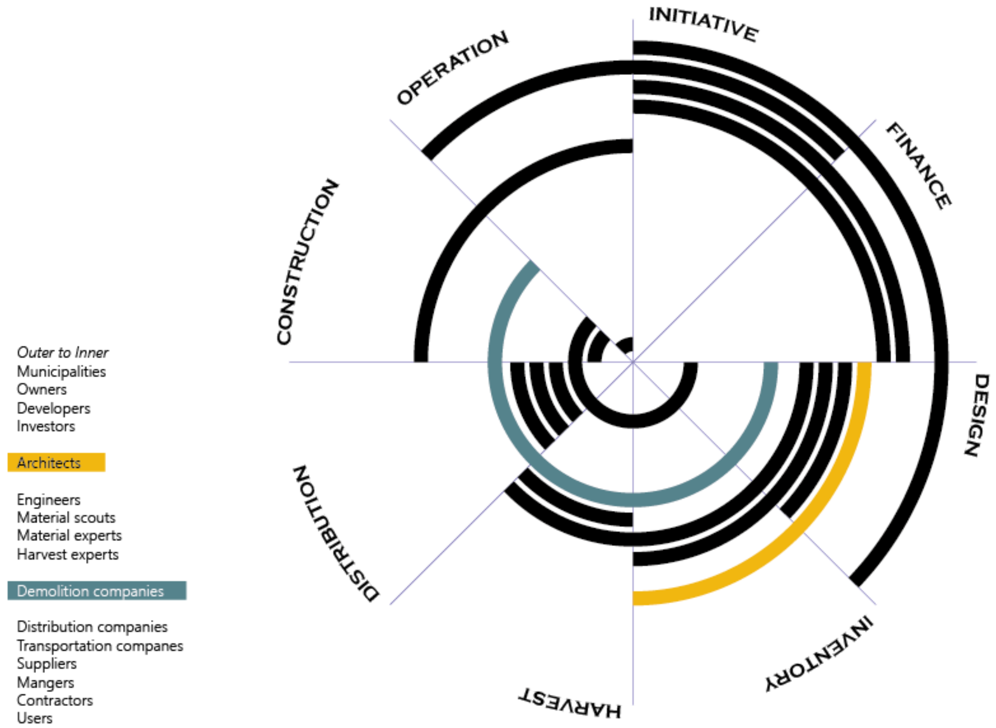

Figure 2.1: Involvement of stakeholders throughout the phases (adapted from UPcycle Amstel, 2019)

This analysis clearly shows the overlap between the active actors. The distinction into phases and actors is harsh and therefore presents a simplified picture of a complex process. However, it allows us to recognise two relevant points for this paper. First; the demolition companies, stretching through four phases, emphasize the significant role from the design up to the construction phase. Demolition companies are the ones with knowledge of demolition processes and recently, also deconstruction methods. Demolition workers, thanks to their 'reverse' knowledge, could function as advisors during the construction as well as offering their insight to benefit the design for future deconstruction. This knowledge exchange is reciprocal, as deconstructors will benefit from a deep understanding of the design and the assembly methods.

The second point is the appearance of the architect in two phases: inventory and design. The implication is the architect being able to promote a transition towards deconstruction and sustainable development during these two phases. In the first phase, by performing iterations on the design, based on an inventory of reclaimed materials. In the second, by creating a design that takes into consideration reuse and end-of-life treatment. Both phases will require information exchange between the architect and the demolition contractor.

To conclude, deconstruction and reuse must go hand in hand. A transition towards common practices of both requires rethinking the role of the stakeholders with the intention of closing loops through communication and collaboration.

2.3 Benefits of Deconstruction

The benefits of deconstruction are the consequence of the joint activity of deconstruction and reuse. The Waste Framework Directive of the European Union presents the following waste hierarchy, from most favourable to least favourable: prevention, reuse, recycling, recovery for energy and disposal. Practice of deconstruction and reuse expresses a circular approach towards use of natural resources as it practices the two most favourable methods in waste management – prevention and reuse (Kanters, 2018). The economic, environmental and social benefits mentioned here are based on pilot projects of deconstruction and reuse (Frisman, 2004):

Economic benefits are the tangible value of the salvaged material that could be sold. In the case of the same owner or developer, reuse of materials on site will reduce costs for new materials. Additionally, the cost for mining and manufacturing could be reduced. Environmental benefits include reducing C&D waste, resulting in less landfill and less toxic waste in soil, air and water. The two other significant factors are the potential in energy saving and the preservation of natural resources. This is for the simple reason that reusing existing materials spares mining, timber-cutting and other energy-intensive processes involved in the manufacturing of new materials. Social benefits include the creation of a new profession, and therefore the creation of additional local jobs. This is for the reason that deconstruction methods require increased labour. Deconstruction enables the integration of a broad range of skills—from basic to specialized. The sector could provide a job training programme in order to form a local skilled workforce. SANDecon in California is a non-profit business that sets its goals to provide professional deconstruction service while addressing local socio-economic issues in the community. By creating employment opportunities within low-income communities, they aim to "*create high-wage, skilled labour jobs and keep money within the local community*" (Munroe et al., 2006, p. 382).

III. Barriers and Challenges in Deconstruction and Reuse

Current barriers relate to either the deconstruction or the reuse phase. In both cases, the main barriers are mostly of economic nature, and often together with current policy, regulation and technical challenges. The conditions do not create sufficient incentives for the stakeholders to shift activities towards the sustainable development of the built environment. This chapter provides first a broader context regarding the dominant economic system and its relationship with the environment. The second section offers a brief overview of the current barriers, often with the provision of possible solutions.

3.1 Profit vs. Environment

".. our economic system and our planetary system are now at war. Or, more accurately, our economy is at war with many forms of life on earth, including human life." (Architektur Zentrum Wien, 2019, p.11)

It is widely discussed in academic literature that capitalism, which thrives on constant growth, stands in conflict with environmental approaches that call for a more sustainable use of Earth resources (Architektur Zentrum Wien, 2019). As many experts, scientists and activists share these ideas, literature offers a wide range of possible alternative analyses which consider benefits and values that go beyond financial profit. One report (Frisman, 2004) stresses that the 'true costs' should take into account environmental costs, which will include for example extracting raw materials, fabrication to products and transportation to site. Another research established a science-based evaluation system - Emergy analysis - to consider environmental, economic and social value: "*Traditional economic analysis based on money cannot be used to find the harmony between economic benefit and environmental effects*" (Yuan et al., 2011, p.2504). They argue further that an analysis of deconstruction and demolition should have a framework that includes '*societal and environmental costs*' rather than merely economic costs. It was said to be a market failure, as the market mechanism does not take into account important factors, besides costs and revenues. Among the important factors that should be addressed are socio-economic impact, pollution and resource conservation (Munroe et al., 2006).

The conclusion is that in the case of deconstruction and reuse a transition is uncertain as long as the current economic system, with a lack of counteracting regulation, continues to create market conditions where demolition is the cheapest option and therefore seen as the favorable practice.

3.2 Overview of the Current Barriers

Deconstruction and recovering materials and components in a way that leaves them suitable for reuse, requires care during the removal process. That care translates into longer duration, need for special tools and skilled, well-trained workers (Munroe et al., 2006). Labour-intensive activity means time consuming procedures, usually several weeks longer than demolition. In financial terms, labour and time translate into higher costs for the contractors.

A Dutch report states another economic-technical barrier which relates to "*the lack of appropriate technical knowledge and information on the feasibility and actual implementation modalities of the deconstruction process*" (Provincie Limburg, 2020). On top of that, the value of salvaged materials from existing buildings is unknown as well as their reuse opportunities. Therefore, it is logical that the market for deconstructed products is not yet established and the consequence is a "*Mismatch of supply and demand in terms of quantity and quality of recovered materials*" (provincie Limburg, 2020, p.1)

Similarly, this is the case in Brussels. According to the Public Service for the Environment and Energy (Leefmilieu Brussel) the obstacles to the reuse of materials include the lack of a real circuit for supply, handling and disposal as well as the need for space and storage. The latter requires a reform of current logistic systems.

Numerous systemic issues stand in the way of a broad practice of building deconstruction. Many among these relate to current policy, regulation and tax systems, as well as norms and codes for building materials. Building codes and regulations regarding the building performance could entail expensive alterations and position demolition as the most profitable (Thomsen et al., 2011). The underdeveloped market, mentioned above, is also the result of restrictive codes and standards. While codes and standards are meant to protect health and safety, they often become regulatory barriers. In the case of using recovered materials, certification might become an obstacle (Munroe et al., 2006). Regulation, on the other hand, can help stimulate deconstruction, by creating incentives. One example is forcing a waiting period, enabling deconstruction to take place, without any 'additional' delay in comparison with conventional demolition.

Public policies have a large influence on demolition practices and currently they often create conditions that result in promoting demolition rather than other alternatives. Policies concerning tax and financial instruments currently stimulate new construction rather than reuse in the form of refurbishment of existing buildings. In the UK, for example the VAT for new construction is zero and tax cost for renovation is 20%. Reform of the tax rates will encourage alternatives and make demolition less viable. Another example is the land policy in the Netherlands. In this case demolition, but not renovation, guarantees the municipality a full coverage of the costs for infrastructure renewal (Thomsen et al., 2011). Another reform suggested is to create a tax system that promotes sustainable goals. The foundation Ex'tax calls to use taxes as a means to achieve an inclusive circular economy by taxing natural resources while decreasing labour taxes (Ex'tax, 2020). Such a reform will stimulate practices of deconstruction and reuse.

An interesting point is the multiple roles governments have, as legislator, enforcer but also as a client. Municipalities and governments could contribute to a more circular behaviour by raising the standards or requirements set by public tenders, as in the case of the project ZIN in Brussels, which will be explained in detail in chapter four.

The main technical and technological challenges relate to deconstruction on the one hand and to reuse on the other. In regard to deconstruction, there is a lack of trained deconstruction workers and specialised tools. At the same time, there is a need for new architectural design and construction practices. The development of new designs and construction techniques will allow the deconstruction of usable components possible (Munroe et al., 2016). In recent years, the use of composite products is widely accepted in order to fulfil the building's performance specifications. These products are harder to disassemble, reuse and even recycle. Similarly, hidden joints between components are difficult to access and deconstruct in a manner that will allow reuse or recycle (Couto & Couto, 2010). In regard to the use of reclaimed building material the main obstacles arise: lack of valid data about the technical composition of the building; quality of the elements; lack of protocols for design and disassembly and lack of instruments for certification of reusable elements (Durmisevic et al., 2017).

Lastly, an interesting point is the "*softer issues of perception, tradition and habit*" (Munroe et al, 2006, p.384). The construction and demolition industry is known to be quite conservative. According to a Dutch report by the Province of Limburg (2020) it is also "*one of the least digitized industries*". The report argues that a digitalization of the construction will be a key factor in the transition towards Circularity. Digitalization will help define deconstruction and reuse strategies for more efficient operation, reuse and high-quality recycling as well as transactions of reusable materials. The extent to which technology is used within the construction industry is provided as a comparison with other sectors (appendix. A).

The benefits of deconstruction and reuse are clear. However, these practices are not yet widely accepted and adopted by the construction industry. The barriers above give a first impression of the complexity in transition towards a circular economic system. The following chapter aims to further explore the technical viability of a certain solution regarding concrete. The technical challenges go together with organisational and strategic aspects such as risk management and proper logistics within the (de)construction cycle. Accordingly, the chapter provides a broad examination of the relevant aspects to the case of deconstruction and reuse of concrete.

IV. The Case of Deconstruction of Concrete

The construction industry in Europe is responsible for approximately 50% of the total natural resources consumption (Durmisevic, 2017) with concrete as the most used building material in the built environment. In construction, the ubiquity of concrete is twice than all other building materials combined (Gagg, 2014). The largest environmental impact of concrete is due to the presence of cement in its composition, "*each year, more than 4 billion tonnes of cement are produced, accounting for around 8 percent of global* CO_2 *emissions*" (Preston & Lehne, 2018, p.1). The production of cement demands large amounts of energy and results in high carbon emission as well as in high embodied energy (Salma, 2017).

Nowadays, recycling of concrete is considered to be circular. However it is important to take into account that the process of recycling involves energy intensive crushing and sorting processes (Akbarnezhad et al., 2014). Furthermore, the transportation of the heavy material to a recycling plant has a significant impact on energy consumption and CO2 emission (Akbarnezhad, 2014). An analysis by Glias (2013) shows high negative environmental impact in the case of recycling in comparison to reusing components. Several different methods of concrete production, according to their use of primary raw materials, primary non renewable energy and related carbon footprint, are shown in the figure below.

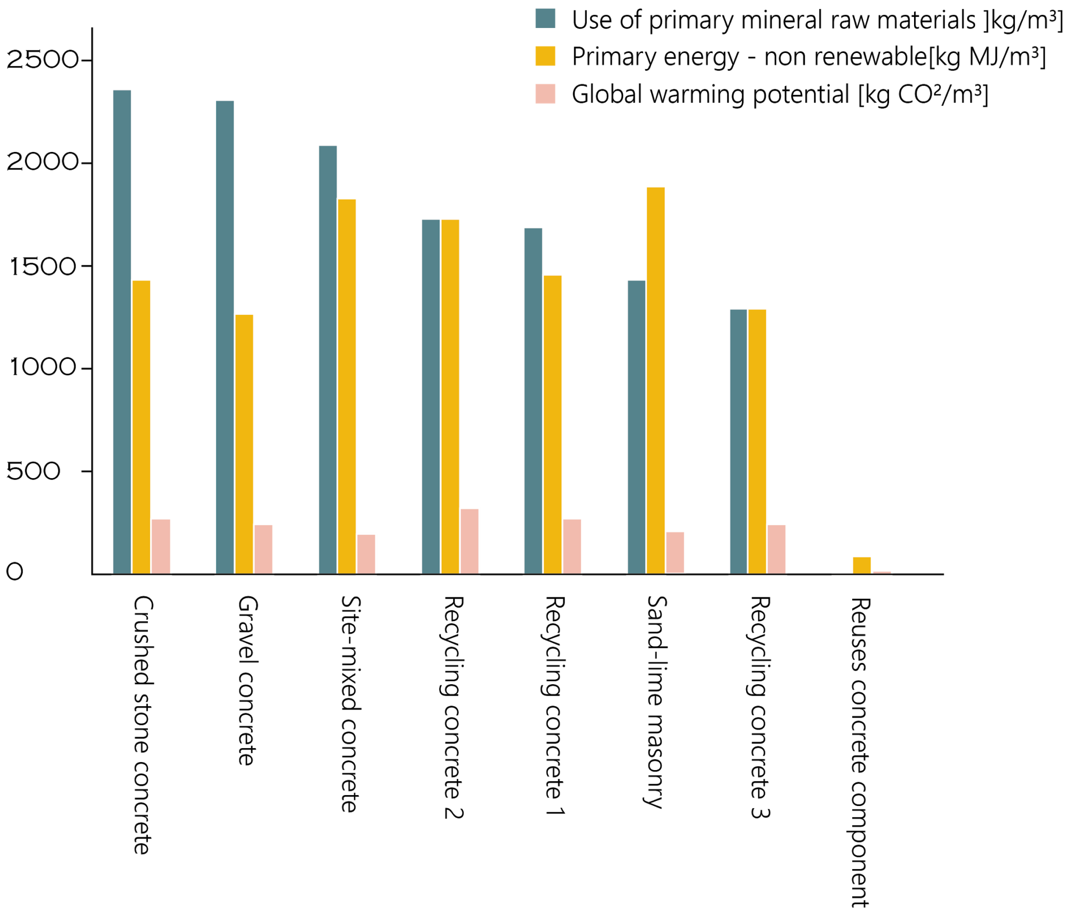

Figure 4.1: Ecological balance comparison of the production of a cubic meter of building material: new, recycled and reused materials (Glias, 2013, p.18)

This chapter introduces a reuse method for concrete as part of an implementation of deconstruction and reuse principles. First, current building stock, waste flows and common practices will be briefly presented to get a better understanding of the potential impact. Then, a method for concrete reuse will be introduced. Finally, it is examined by an energy comparison analysis based on a (hypothetical) case study located in Brussels, Belgium.

4.1 Current state

The first step, before offering an alternative, is understanding the current situation and procedures. The following sections will investigate two main aspects in the current state: the ubiquity of concrete and its current end-of-life treatment.

4.1.1 Existing building stock

Despite concrete being the most common construction material around the world, and has been for the last few decades it is in a period of transition towards circular systems within the built environment, it is often overlooked (Couto & Couto, 2010). Currently, most of the interest regarding recovered materials lies in high value, low volume streams (unique items) rather than in concrete, which has high volume and low value due to the relatively low cost of new concrete. The high volume of concrete could become an advantage when aiming to create a stable supply chain of concrete components for reuse. The fact that many tall buildings built in the 20th century are now facing their end-of-life phase (Council on Tall Buildings and Urban Habitat, 2014), makes the deconstruction of tall buildings with steel reinforced concrete structural frames especially relevant. In figure 4.1 the trend of structural materials in tall buildings demonstrates the constant growth in use of concrete (Ali

& Moon, 2018). While composite refers to a combined steel and concrete system, mixed is a distinct system of both. This means that developing a system for reuse of concrete (in combination with steel rebar) will have an impact today as well as in the future when contemporary buildings will reach their end of use phase.

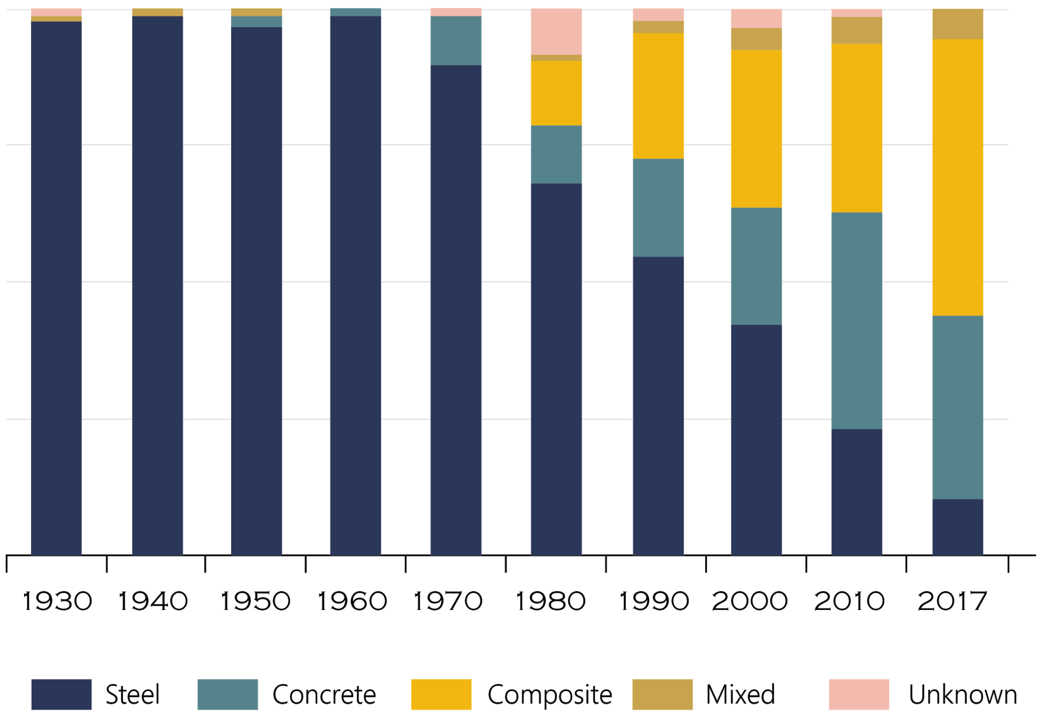

Figure 4.1: Tallest buildings by structural material (Ali & Moon, 2018).

An additional aspect to be considered is the variety in types of concrete structures. An initial distinction is between in-situ cast and precast concrete. The first, being cast on site, forms a monolithic structure and permanent joints. The second refers to components that are made in a controlled environment and brought to the site. However, precast will usually be combined with in-situ to create permanent joints as well. Precast elements which can be deconstructed and reused in a new construction do exist in the market. One example is the company CD20 in The Netherlands. The concept of reusable precast elements is the subject for research in various projects (Salama, 2017). Nevertheless, the possible reuse of existing in-situ concrete is not yet explored in literature nor in documented practice. Therefore, the focus here is structural frames of tall buildings constructed with in-situ concrete.

When an inventory and assessment of structural concrete is made, it is important to acknowledge the different types of concrete that were used in different periods. Looking specifically into the history of concrete structures in Belgium, one can learn about the changes over time through the regulatory framework. From a comparative study by van de Voorde et al., (2017) regarding the early regulations on reinforced concrete, it is shown that a regulatory framework in the form of advisory guidelines was only formed in 1923 (appx. B). These advisory instructions concerned basic design rules, calculation methods, and the execution and control of reinforced concrete construction. This was the case until 1953, when the European Committee for Concrete (CEB) initiated the transition from national regulations to international norms and standards, eventually resulting in the Eurocodes from 1990 onwards. This information can assist when performing an assessment of existing concrete. Currently in Belgium the EN 206, including ongoing revisions, is the active European norm. Further specification and standards are provided in the Belgian NBN EN 206 (Eurocodes: Building the

Future, n.d.). The relations with other standards, based on the latest version of 2018 (Norm NBN, 2020), are provided (appx. C).

4.1.2 Current flow of concrete

Concrete is considered part of the inert waste stream. In terms of weight, the inert waste, which consists of stoney materials (concrete, bricks, ceramics and natural stone) forms 90% of the total C&D waste in Belgium (OVAM, 2013). The recycling rate for inert waste in Belgium is approx. 84% (European Environment Agency, 2020). The process of concrete recycling (appx. D) includes the manufacturing of a high quality recycled concrete aggregate (RCA) for use in a new concrete structure. The new concrete will require the addition of new cement. Again, this is an exception as the largest part will be downcycled, which means the recycled material will "*be used in a lower grade application compared to the initial application*" (Akbarneshad, 2014, p.131). For example, an aggregate for roadbeds. It is worth mentioning that European codes currently allow a maximum of 30% RCA in the production of new concrete, before a further proof of quality is required (GMB, 2019). The reuse of concrete and other stoney materials mentioned above can be distinguished into the reuse of a whole building, for example renovation, or in the scale of components such as reuse of roof tiles. The two scales of reuse are quite uncommon currently for concrete.

Great deal of research has been focused on recycling of concrete and the various procedures available. While these aspects will not be discussed here, a relevant body of literature was used to perform the energy analysis comparison in the following section.

4.2 Deconstructing concrete and potential impact

Based on the arguments presented above, a proposal regarding the reuse of structural in-situ concrete is introduced. The proposed method is to be seen as a part of a complete deconstruction operation. The method involves cutting the steel reinforced concrete structure into standard elements which can be reused to extend their service life without further processing. The idea is to avoid further manufacturing and the addition of new raw materials. The cut components could be considered as 'ready-made' components in terms of use in new construction, assembly, transportation etc.

In order to explore this idea, a series of interviews was conducted (appx. H) in addition to research into existing techniques, various requirements and main challenges to be addressed. In the following section the idea is explained in greater detail based on a hypothetical case study in Brussels. As the method has two different technical and managerial phases, there will be first a focus on the cutting phase followed by several first insights into the reuse phase of the 'ready-made' components.

The potential impact lies in lowering embodied energy in new construction by deconstruction and reusing existing buildings and their materials and components. In recent years there is a focus in European countries on the energy performance requirements of the building during its operation phase. It is however equally important to ensure low embodied energy of the building. The embodied energy might be equal to the energy consumption when comparing over a building's lifespan of 50 years (kanters, 2018). Moreover, some buildings will not reach such a lifespan.

4.2.1 From building to building component

This section aims to outline the whole procedure and define its conditions. As mentioned, this section is based largely on interviews with several academics, with various expertise in construction and concrete. It was concluded that cutting concrete is possible from a technical examination. The input from the interviewees was mostly related to pragmatic ways to integrate the method into the market in regard to incentives to attract stakeholders as well as the challenges in reusing the components, in terms of certification, norms and codes.

The integration of new practices within the construction industry is complex and relates to the multiplicity of stakeholders, their interest and the possible economic incentives. This section offers an initial overview of the different phases in the procedure of cutting and reusing concrete as shown in fig. 4.2 (appx. E for a larger version). An alternative material flow requires the involvement of the different actors within the (de)construction industry. In each phase several main points that will require further research and experimentation are mentioned and should be executed by relevant disciplines, such as engineering, material experts and demolition workers.

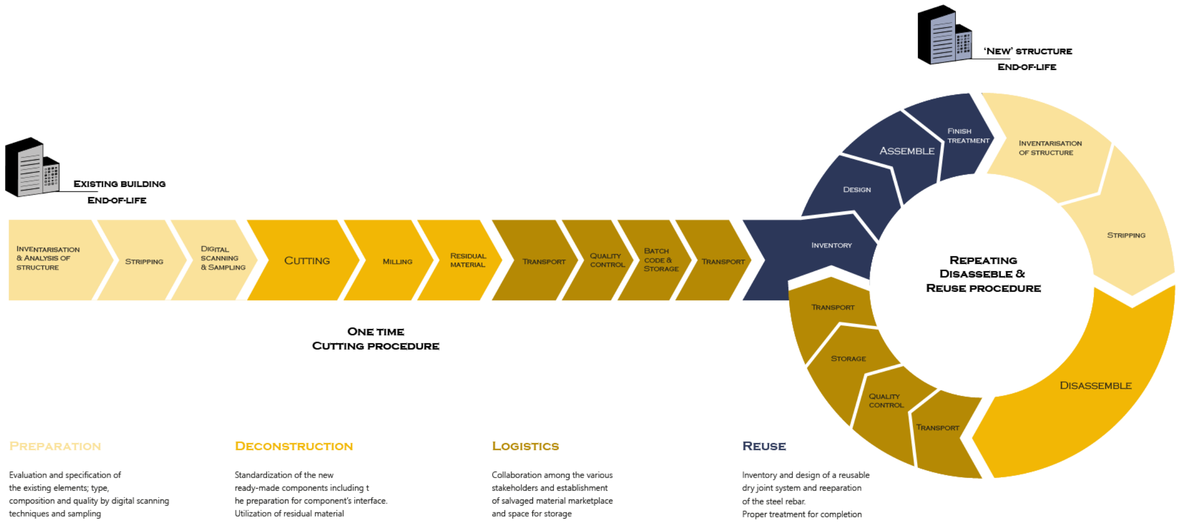

Figure 4.2: A steps diagram: building to building component

The proposed system has to be developed to enable a specific work method for each of the main existing structural elements, as presented in the table below. The table includes possible measurements to be standardized in the case of the WTC towers, according to the restrictions of the original structure (appx. F.1):

Structural element	**Fixed measurements**	**Possible component**	**Measurements**
Column	Cross-section of the profile Floor height	Column	h=3m
Floor slab	Slab thickness	Floor slab or a wall component depends on original rebar position	b×l= 7.5m×7.5m; 7.5m×3.75m
Beam	Cross-section Column grid	Beam	l= 7.5m
Shear wall	Wall thickness	Wall	h×l= 3m×7.5m; 3m×3.75m
Core	Thickness and dimensions of cross-section	Core or a smaller wall component	-

In a more general sense, elements such as the beam and column should be cut to form the longest or highest component possible to allow maximum flexibility in the reuse phase. Maximal length should not exceed 13.5m due to limitations of transport in Europe (Larsson, 2009).

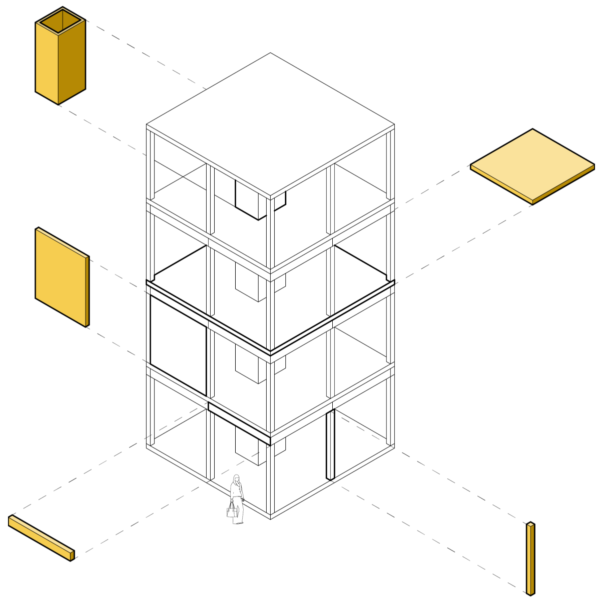

Figure 4.3: the main existing structural concrete elements

There is a great importance in recognizing the quality and type of the concrete, as well as the steel rebar, prior to the deconstruction and reuse. This is important both in the case of reuse as load bearing or non-load bearing. The process of assessment is part of the preparation phase and can utilize digital scanners to provide reliable information about the available concrete (Knaack U., personal communication, October 28, 2020). Such a procedure of sampling and analysis was performed in the ZIN project in Brussels. Moreover, the process of creating the ready-made components has to include milling of each component for future interface with other components and the repairing of the steel rebar to withstand tensile forces. The treatment could be distinguished between load bearing components and non-load bearing. The load bearing component requires a thin layer of concrete to avoid exposure of the rebar and cracking of the concrete. The non-load bearing could be eventually treated with a layer of paint to cover the exposed steel and avoid corrosion. For the repairing of the steel reinforcement two techniques, a chemical or mechanical anchoring, should be considered. This will require tests and therefore the involvement and advice of a structural engineer (Yang, Y., October 23, 2020). The treatment of residual material (unusable after cutting) will have an apart processing, assumed here to be processed into RCA, to be later used for the cover of steel rebar.

From a regulatory standpoint, building codes might have to be reconsidered. This will require a collaboration of public authorities, building industries, academia, private entrepreneurships and professional bodies. Together with improvement of the logistics, including batch code and storage, a new market, with stable supply, could be established.

Based on the stakeholders analysis presented in chapter two, in the case of the concrete the involvement of actors will include the demolition company, architect, contractors, engineers, municipalities, government, distributors, manufacturer and the client. Each of the actors plays a role in 'their' supply chain, either during the deconstruction phase, the design phase, the reuse and construction or the logistics, as storage and transport. Several examples of actors' contributions towards the integration of the reuse system is briefly presented here to demonstrate the complexity and multifaceted character of the transition towards deconstruction and reuse. These examples emphasise that the transition must be approached from different directions simultaneously.

- Currently, the recycling of building materials in Brussels is obligatory. The municipalities in Brussels could decide to extend this requirement to include a minimum percentage of material to be reused, for example to set a requirement for at least 50% of the volume of the existing concrete to become reusable.

- In the case of clients, whether private or public, they could set high standards for circularity in terms of materials and energy consumption. Specifically, in the case of tenders. An example is a requirement to incorporate a minimum of 30% reused materials and components.

- The concrete industry and manufacturers of concrete could offer a long-term service instead of the one-time purchase of a product.

4.2.2 Available cutting methods

Research shows that there are currently two available methods for cutting steel reinforced concrete. It is important to note that none of these methods are currently used with the intention to reuse the cut concrete elements. Usually, these techniques are used for renovation and reparation of structures or roads. The two techniques are briefly introduced and will form the basis for the energy analysis.

I. Diamond circular saw blades. The blades could be used in various machinery, from hand operating to 'walk-behind' semi-automatic machinery. While a smaller machine is powered by electricity, a larger one will require fuel. A common way of manufacturing is vacuum brazed diamond saws that will cut through the concrete as well as the steel (Desert Diamond Industries Frequently Asked Questions Page, n.d.). The diamond saw creates the cut by grinding the material through an action of friction. Additionally, water is often used during the process to avoid overheating of the saw and decrease dust. The cutting speed can vary, but we will assume 50 m/h when cutting a floor, 200 mm thick, with a machine operating with fuel (Walk Behind Saw - Sawing - Products, 2020).

II. Abrasive water jet (AWJ). This technique performs cuts by using ultra high pressure water mixed with sand. The traverse speed (cut speed) varies based on the thickness of the material, the operating pressure, water flow rate, the quality and quantity of abrasive, the shape to be cut and the desired edge finish (Hydro Cutting Concrete, 2019). The traverse speed is assumed to be 5m/h, based on videos demonstrating cutting concrete (Cutting Concrete With A 60,000 PSI Waterjet, 2017; Water Jet Cutting Huge Concrete Slab, 2020). It is assumed to have a pressure equal to 90,000 psi (highest found by manufacturers) in order to cut a wall with a thickness of 150mm (Wright, 2016). Additional aspect of the use of AWJ is the possibility to combine the cutting method with CAD and robotic machinery. This can be utilized to improve precision in the creation of standardized components (Hydro Cutting Concrete, 2019).

In the following section an estimation of energy consumption is made as a first step to check the viability of the cutting methods in comparison with recycling processes of concrete. While both methods use water for cooling, dust reduction or even the cutting itself, the AWJ requires another resource, sand, as the abrasive. In both cases, sludge and slurry are produced as a result of the cutting. These aspects are not taken into account in the following analysis of energy consumption. Additional analysis of water and sand usage is needed as well as the potential in upcycling the sludge and slurry.

4.3 Energy consumption analysis

The potential saved energy by reusing concrete is examined here based on a (hypothetical) case study in Belgium. The deconstruction of the World Trade Centre (WTC) towers in Brussels will take place in the coming years. The real estate developers, Befimmo, won a tender thanks to an advanced circular approach towards design and material use. While the Flemish government, as the client, requested a maximum percentage of new materials with cradle to cradle certification, the proposal included a complete deconstruction and reuse of 64% of the building material (Appx. F.2). Additionally, the building is energy neutral and its programme allows flexibility. During the planning phase, after a comprehensive analysis, it was decided to leave the concrete superstructure - lower levels and lift shafts - in its original state (figure 4.4).

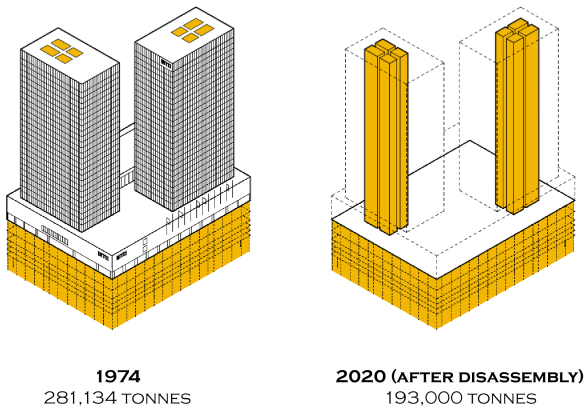

Figure 4.4: The remaining structural concrete after deconstruction. Provided by Befimmo (2020)

The rest of the concrete, from other parts of the towers, will be transferred for processing at the crushing plant ABR, located nearby, for the recycled material to be transported back and used on site for the new construction (as screed). The method of reuse was chosen because it is optimal in terms of conservation of embodied energy (Couto & Couto, 2010). For the purpose of an energy estimation, a hypothetical situation is defined, where the two following options are offered:

1. Recycle. The entire concrete structure is demolished and directed to a crushing plant to be recycled into high quality aggregate to be used in the production of new concrete for construction on a second site. The two recycling processes, wet and dry, are included in the comparison (Rakesh, 2019).

2. Reuse. In this case 75% of the structure is cut into usable components and transported directly to the second site for reuse. The two methods of cutting are included. The remaining 25% is being crushed onsite and then transported as well to the second site for the production of new concrete.

While the first option requires off-site crushing due to the great volume (~200,000 tonne), the second option, approx. 25%, is assumed to be processed onsite. Mobile on-site crushing will mean less transport but will result in lesser quality of the aggregate. (Dardis, 2012).

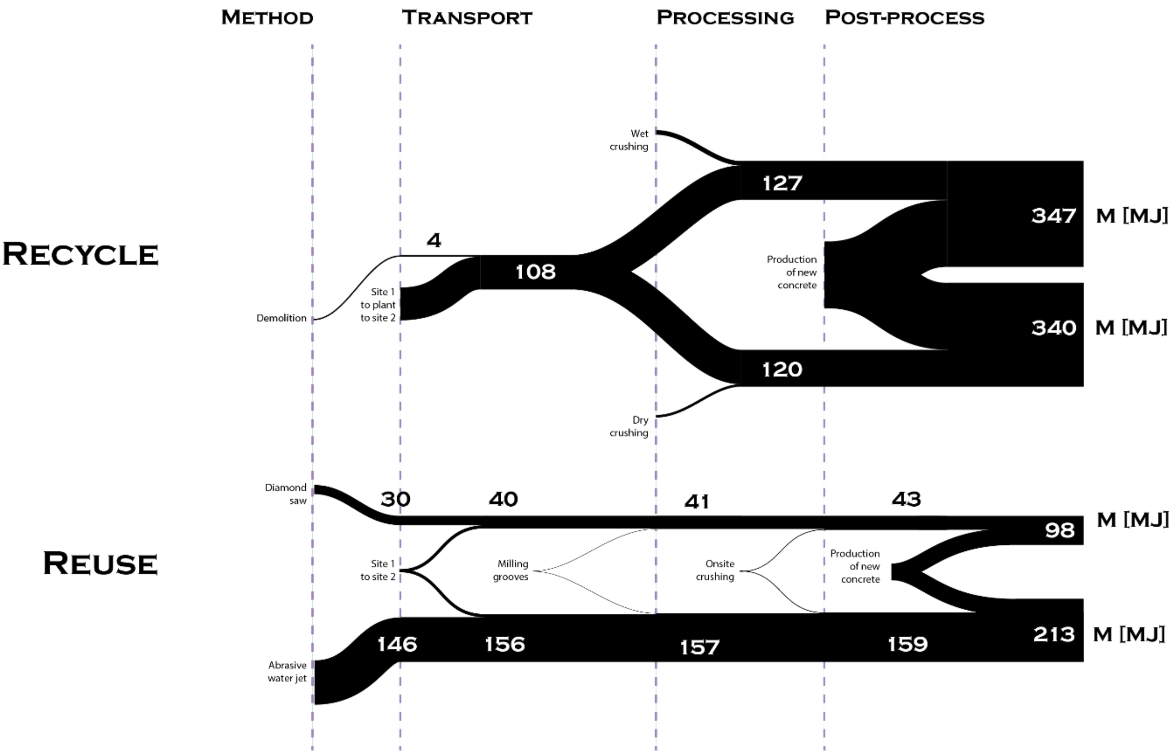

Figure 4.5: Energy consumption comparison reuse vs. recycling

The comparison shows that the production of new concrete is the most energy intensive phase in the recycling process and up the production of usable new concrete. In the case of cutting, however, this is drastically reduced. Here, the largest portion of energy demand is in the cutting phase. This analysis demonstrates that by reusing concrete, the embodied energy of a building can be lowered, by approximately 70%. Further clarification with the data for this diagram can be found in the appendices (appx. G).

This change may arise in different phases of the chain, however the most fundamental change would take place once the demand from clients, together with supportive regulation towards circular practices, and adjustment of the design process have evolved simultaneously. Additional support systems will be needed from a logistic point of view, such as storage, sorting and transport of the recovered materials. Once practices of deconstruction, and possibly deconstruction of concrete, are widely accepted, the market will, in turn, transform and increase the feasibility. Yet, broad social, economic and environmental considerations should be taken into account. That will require, for example, performing several analyses measuring potential impact of energy, natural resources and waste.

V. Conclusion

This paper outlines the various aspects of reusing deconstructed buildings, specifically ones built of concrete, as valuable resources in order to offer a viable alternative to the prevalent yet ecologically unsustainable mining. It aims to provide a holistic image of the current state of affairs, and consider the transition towards deconstruction from theoretical, practical and spatial standpoints. As discussed, deconstruction and reuse must go hand in hand, and therefore, a more substantial progress requires the involvement of numerous stakeholders, who must all be committed to closing the chain of the construction material and replacing the current system with a circular one. Although the current economic system, which sets profit as its only measure, poses systemic challenges for such a transition, technical exploration would nevertheless be beneficial for its advancement as it contributes to a body of knowledge that may affect regulators and decision-makers, thereby stimulating the creation of more favourable market conditions.

The method proposed in this paper is to cut in-situ structural concrete into ready-made components to be reused in new construction. Based on a case study in Brussels, the WTC towers, a set of possible components was provided with their specific measurements, which are determined by the original structural frame. This set of components formed part of the inventory for the design and construction of the second site.

Subsequently, the paper demonstrated that by cutting concrete using a diamond saw, this proposed method could cut the consumed energy by approximately 70%, in comparison with a wet recycling process of the same volume. The abrasive water jet was shown to be less energy-efficient than the diamond saw, yet more efficient than recycling. However, in terms of human labour, this method, in contrast to diamond saw, can be combined with advanced technologies that will support a standard universal procedure. Accordingly, several technical issues should be further explored in terms of the natural resources needed for both cutting methods, as well as in terms of the treatment and utilization of the residual material.

The potential impact of such development is clearly significant as concrete is a dominant material in our built environment, with an annual production of 33 billion tons. While cutting concrete is technically viable, making it economically viable will take time and require a radical change in our current economic approach towards natural resources. The transition to a complete deconstruction and optimal reuse of concrete must arise within different phases of the chain. A fundamental change would include a change in client demand, circular-oriented regulation, and adjustments to the traditional design process, logistics, and flow of material. In regard to design, the architect will adopt the extended responsibility of taking construction and deconstruction into account during the design phase. An example for a responsible practice could be a collaboration with demolition companies, which would ensure a circular material flow.

Finally, a standard method for reuse must be developed in order to introduce the system to the market. Ideally, this would be a collaboration between different actors such as architects, engineers, demolition companies, and real estate developers. The aim should be the development of a standard product with a high feasibility and large scale impact. Further research and testing will determine the feasibility of the system as a whole, and predict the consequences such a system may have if adopted as common practice.

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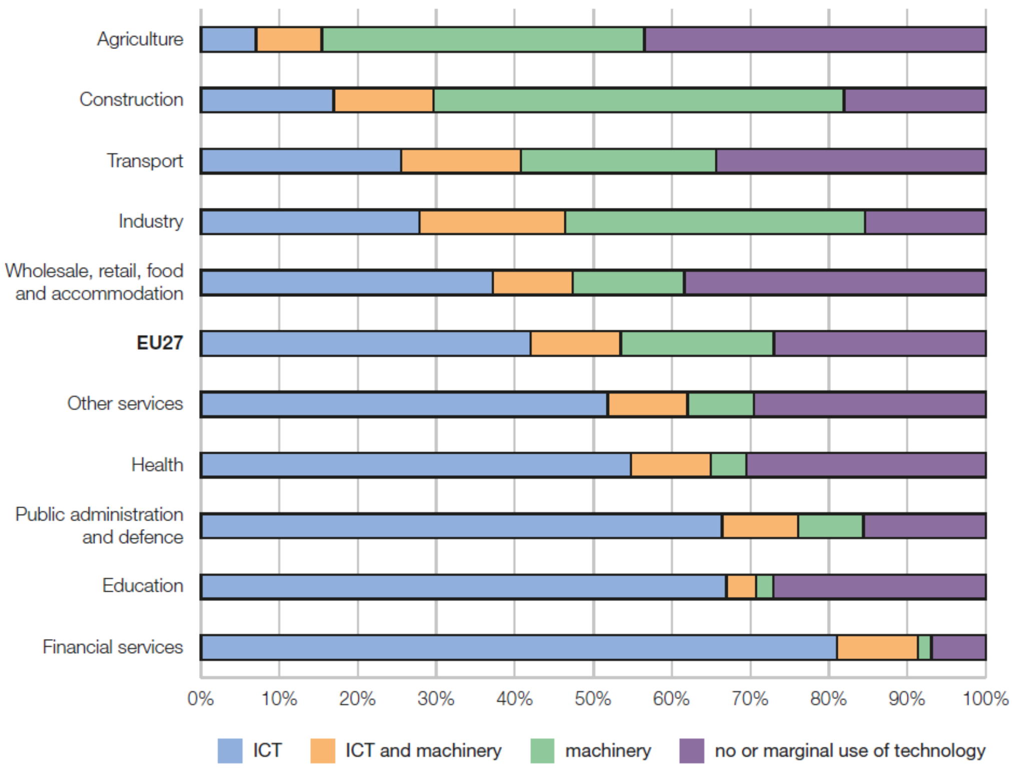
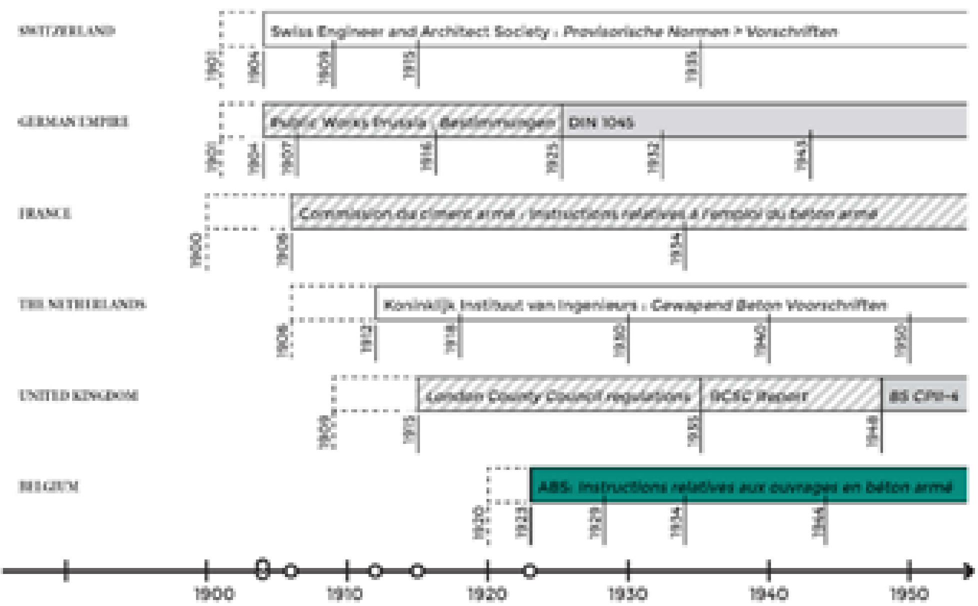
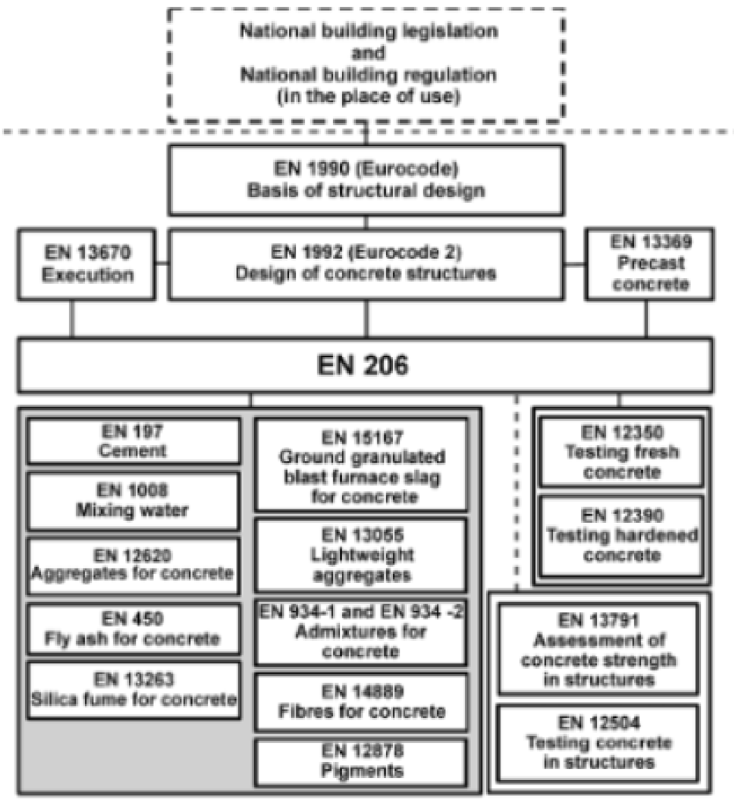
Appendices



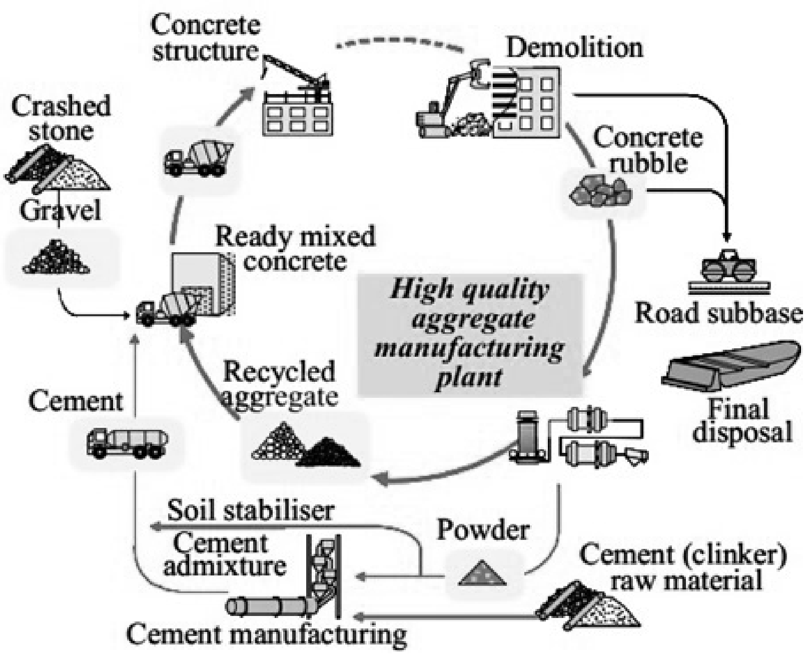
Appendix A: The extent to which technology is used within various sectors ((Eurofound, 2012, p.68)



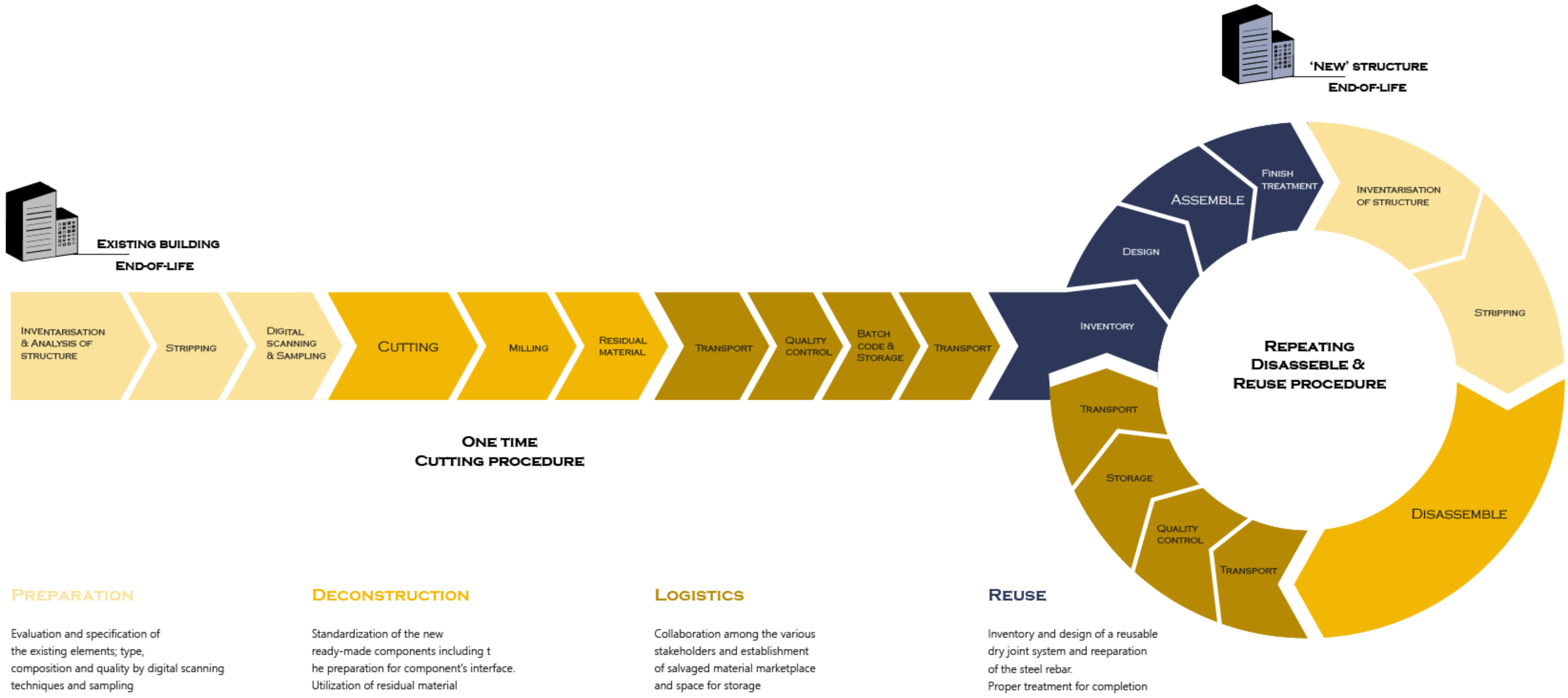
Appendix B: Early Regulations on Reinforced Concrete (van de Voorde et al., 2017, p. 353)



Appendix C: relationships between EN 206-1 and standards for design and execution, standards for constituent materials and test standards (NBN, 2018)

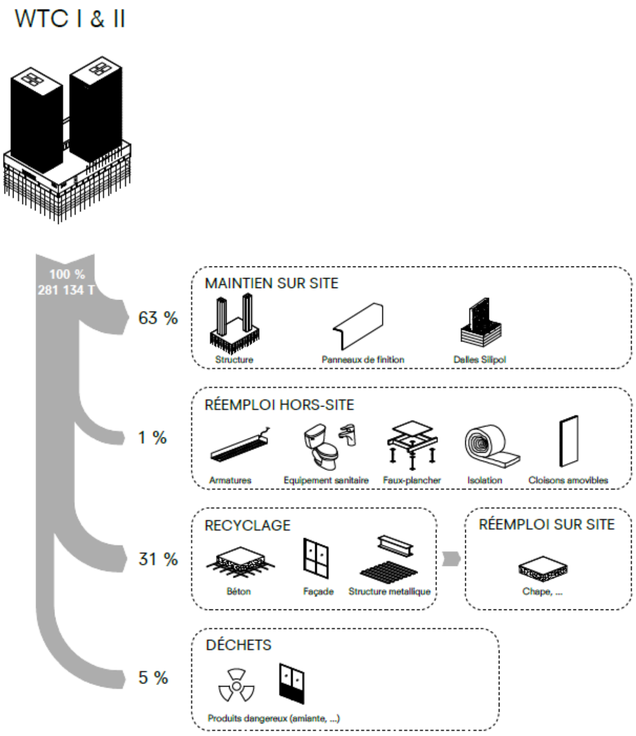


Appendix D: Process of Waste Concrete Recycling (Ganiron, 2015, p.9)



Appendix E: A steps diagram: building to building component

Appendix F.1:Example for standard components based on the original structure and its grid (floor plan provided by Befimmo, 2020)



Appendix F.2: The WTC towers material flow. Provided by Befimmo (2020).

	World Trade Center									
	Volume of cocrete (base+Shafts)	200,000	tonne							
	Total Surface	108,500	m^2							
Recycle										
Action			Units	comments		total	Units	Total	Units	Source
Demolition		2352/2300	liter/m^2			112,896	Liter fuel	4,369,075	MJ	Rakesh & Keshava (2019)
Transport site to plant		0,39	liter/km	Distance WTC to close breekinstallatie (**16km**)per 1 tonne		1,248,000	Liter fuel	48,297,600	MJ	Dardis (2012); www.all-belgian-recycling.be/
Processing										
	option 1: Dry crushing	37	MJ/tonne			7,366,000	Liter fuel	7,386,000	MJ	Rakesh & Keshava (2019)
	option 2: Wet crushing	72	MJ/tonne			14,386,000	Liter fuel	14,386,000	MJ	
Transport plant to new site		0,39	liter/km	Distance ABR breekinstallatie to site (29km) per 1 tonne		1,560,000	Liter fuel	60,372,000	MJ	
										https://www.geoplastglobal.com/en/blog/energy-consumption-production-of-concrete/#:~:text=The%20production%20of%201%20m%C2%B3,by%200.37%20barrels%20of%20oil.
Making new concrete onsite		1,100	MJ/tonee					220,000,000	MJ	http://www.planete-tp.com/en/concrete-mix-design-a221.html#:~:text=One%20cubic%20metre%20of%20concrete,and%20150%20Litres%20of%20water.
					Total Dry	**10,286,896**	Liter fuel	**340,424,675**	MJ	
					Total wet	**17,306,896**	Liter fuel	**347,424,675**	MJ	
Reuse										
Action			Units	comments		total	Units	Total	Units	
Cutting										
	option 1: Cutting diamond saw	4	Liter/tonne	using a walk behind machine with 74 hp. cut speed (assumed) 50m/h?		800,000		30,960,000	MJ	
	option 2: Cutting Abrasive water jet	25,2	Liter/tonne	Traverse speed assumed 5m/h (10% of diamond saw)		3,780,000	Liter fuel	146,286,000	MJ	
Milling grooves		0.1	Liter/tonne	will be made also with a diamond saw				430,500	MJ	https://www.indiamart.com/diamondengineering-ahmedabad/concrete-groove-cutting-machine.html
Transport		0,39	liter/km	site 1 to site 2 - 3.5 km (check possibility on water?)		273,000		10,565,100	MJ	
residual crushing on site		1	Liter/tonne	75% usable for component and 25% goes to onsite crushing		54,000	Liter fuel	2,089,800		
Making new concrete onsite		1,100	MJ/tonee					55,000,000	MJ	http://www.planete-tp.com/en/concrete-mix-design-a221.html#:~:text=One%20cubic%20metre%20of%20concrete,and%20150%20Litres%20of%20water.
					Total Diamond	**4,107,000**	Liter fuel	**99,045,400**	MJ	
					Total Abrasive		Liter fuel	**214,371,400**	MJ	
	Alternative calculation for abrasive :			966MJ ; v= 5m/h ; 3.6h work			Liter fuel	144,900,000		
	Notes									
	Resource needed as abrasive is not talken into account									
	Water [wet process; Diamond saw, Water Jet]									
	Sludge/slurry - could come back into the cycle									
	milling the components to make interlocking or chemical anchoring should be addressed									
	Manual labour is not included here									
	Additional - procedure and safety when cutting down floors/coloumns/walls									

Additional Calculations

Cutting diamond saw				Milling								
	1.5L/h		74hp=55kw	2	kW							
			6L/h	1	liter	9,1 kwh						
Floor 200mm	14m cutting		50m/h	12	m							
	100-120m/h		4L	50	m/h							
				0,5	h							
https://sydneytools.com.au/product/husqvarna-k1270-5-8kw-400mm-16-concrete-saw				0.2	L/h							
				0.1	Liter/tonne							
Cutting Abrasive water jet		**wall - 150mm**	Alternative calculation									
94,000PSI	75kW		100 horsepower	convertor	0.0745	MJ/s	268.2	MJ/h	965.52	MJ	https://www.engineering.com/PLMERP/ArticleID/12716/An-Engineers-Guide-to-Waterjet-Cutting.aspx	
85%											https://www.traditionaloven.com/tutorials/energy/convert-horsepower-hour-hp-h-to-mega-joule-mj.html	
	63.75	kW										
1 litre of petrol = 9,1 kwh		kwh			36	Liter/h	216	Liter	8359.2	MJ		
	7	liter/h										
Traverse speed of cutting	5m/h			diesel engine burns about 0.4 pounds of fuel per hour for each unit of horsepower it produces							https://www.boatingmag.com/calculating-fuel-consumption#:~:text=On%20average%2C%20an%20inboard%20[illegible]	
1 tonne of wall will be 18m cutting			180	g/h/hp	18000	g/h	24	L/h	144	L	55728	MJ
	3.6	hours										
	25.2	liter/tonne										

https://aceutting.com/products/dp-5801290?variant=15055075967025
https://www.cedima.com/en/Diamond-tools/Diamond-saw-blades/Beton-Plus.html

Appendix G.1: Data For the energy analysis

- Quality control, batch code and transport to storage are not taken into account as it assumes the material all goes to site 2 - in reality it won't be possible (maybe 10% procent will go to site) then it means 10 other similar sites will be needed.
- While not taken into consideration, sand and water are used in the process of abrasive water jet. These are the same finite resources required for the production of new concrete.
- Transport of concrete, as it is very heavy, has high energy consumption. As one truck can transport about 16 tonne (~7 m^3 concrete), numerous rounds are usually needed to transfer the concrete to the crushing plant. In this case, the plant is situated only 16 km further away from the site. However, this is not always the case and often the demolished concrete will be transferred larger distances.
- In terms of energy- additional procedures, such as cranes to ensure safety, should be taken into account when cutting horizontal surfaces.
- The reuse of slurry and sludge resulting from cutting should be further researched.
- Manual labour, in terms of conditions, level of skill and time is not considered here.

Appendix G.2: Clarification and comments regarding the energy analysis

Appendix H includes the seven interviews in the following pages