MASTER THESIS

Value Retention: Preconditions for Moving from Demolition to Deconstruction

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April 2020

UNIVERSITY OF TWENTE.

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ABSTRACT

Currently, 95% of the construction waste is recycled, but 70% of this recycling can actually be defined as downcycling. This implies a massive loss of value, which can be altered by moving towards deconstruction instead of demolition. This research looks into the preconditions for this transition. The goal of the research is to analyse the most important preconditions per value retaining deconstruction strategy. Literature research, validated by case studies, generated eight main preconditions. Three categories are identified: direct influence, future influence and sector influence. Direct influence means the preconditions can be met in present projects by an individual construction company and contains preconditions 'building sequence information is archived to share with future demolition contractor' and 'storage facility is available'. Future influence means construction companies can take action now, to meet preconditions in the future and contains preconditions 'certainty on deconstruction time and recovery rate', 'objects are relatively easy to deconstruct', 'elements with standardized dimensions' and 'material is of high quality'. Sector influence means actions of the whole construction sector are necessary to meet the preconditions and contains preconditions 'second hand materials are demanded' and 'financial case is clear and profitable'. Lastly, in the case studies, the deconstruction strategies (reuse, remanufacture and recycle) are used parallel to each other.

Key words: Value retention, Deconstruction strategies, Preconditions, Existing buildings, Circular Economy.

1 INTRODUCTION

Our current linear socioeconomic system, characterized by the product discard at the end of product life, is one of the main causes for the recent period of severe natural depletion (Michelini, Moraes, Cunha, Costa, & Ometto, 2017). The key issue of this economy is the linear (one way) throughput flow of materials and energy between nature and human economy (Korhonen, Honkasalo, & Seppälä, 2018). This linear throughput is currently seen as the main creator of value and therefore the creator of welfare (Michelini et al., 2017). While ever more raw materials and energy are prolonged by mankind, the earth can only offer a limited amount (Brown, 2006).

The Dutch construction sector produces most waste of all Dutch sectors with 24 million tonnes of waste on a yearly basis, which is about 40% of the total waste production (Rijkswaterstaat, 2013). This amount of waste production translates into a stake of 5% of the CO2 emission (HEVO, 2018). A large percentage of the waste, 95%, is recycled, but about 70% of this recycling can actually be identified as downcycling (Van Odijk & Van Bovene, 2014). This is because the materials are no longer available for the high-class supply chain but must be used in a lower class. When repeating this process, the material will repeatedly be downcycled and eventually become waste. A circular approach aims to retain value and therefore focusses on reusing materials as high-class as possible.

Governments and institutions try to stimulate reuse because of the intuitive belief that it reduces both new production and waste production (Silva, De Brito, & Dhir, 2017). The European Union and The Ellen MacArthur Foundation are calling for a new economic model, as can be seen on the Europe 2020 strategy: "the European Union has no choice but to go for the transition to a resource-efficient and ultimately regenerative circular economy”. This highlights the trend for a circular economy (CE), characterized by restoration and circularity of product components. The World Economic Forum published a report in 2014, in cooperation with EMF and McKinsey where a comprehensive definition for CE was developed: “A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models” (World Economic Forum, 2014).

Unfortunately, most of the information about circularity is rather scientific and does not combine with practical solutions, therefore companies are still searching on how to adapt towards a circular economy (Korhonen et al., 2018). But there is a lack of frameworks to change into a circular business model and the current approach mostly contains an on/off approach and no way in between (Urbinati, Chiaroni, & Chiesa, 2017). In the field of deconstruction strategies there are some ambiguities to. A distinction between short and long-life materials is proposed. Where the short life materials should be taken back by their supplier and the long-life materials can be traded at a material marketplace (Leising, Quist, & Bocken, 2018). Whereas another study suggest it is best to first look local, to reuse materials and then look into selling and usage at another place. This is because transport of materials can be of a big influence regarding circularity (Nasir, Genovese, Acquaye, Koh, & Yamaoh, 2017). Van den Berg, Voordijk & Adriaanse (2019b) used the end of life options: Separating, Moving and Selling. While Iacovidou & Purnell (2016) identify the following deconstruction interventions: Adaptive reuse, Deconstruction, Design for Deconstruction, Design for reuse & Design for manufacture and assembly. Another distinction is made in the shape of: Disposal, Recycling, Remanufacture & Reuse (Korhonen et al., 2018). In general, al lot of different deconstruction strategies are mentioned, but there is no clarity.

When clarity on the deconstruction strategies is achieved, it is important to know how and when to execute the different strategies. Which can be explained as the preconditions for deconstruction strategies. At a conceptual level some preconditions are identified and some directions for solving those problems are given. Nasir et al. (2017) conclude economic implications are the main challenge for implementing CE. This is supported by Van den Berg, Voordijk & Adriaanse (2019a) who state one of the three major conditions for disassembly, is the demolition company identifying an economic demand. A lack of market mechanisms to aid greater recovery and an unclear financial case are preconditions for implementing the circular economy (Adams, Thorpe, Osmanin, & Thornback, 2017). Other preconditions are to distinguish disassembly routines and to control future performance of the elements (Van den Berg et al., 2019a). Important preconditions are both the environmental and economic viability of the to be used solutions (Pomponi & Moncaster, 2017). Mangla, et al. (2018) identified barriers for effective circular supply chain management in a developing country context. Mahpour (2018) identified and prioritized 22 potential barriers for moving towards a CE in construction and demolition waste management, a limitation mentioned here is that the list is not expected to be complete. Construction and demolition waste management is evidently very close related to the process of demolishing a building, which is the reason why this research is mentioned. In the infrastructure industry barriers are also identified (Iacovidou & Purnell, 2016), which again is closely related but not exactly focussed on the construction industry in terms of buildings. It is recommended to further explore possible barriers for implementing a CE (Mangla et al., 2018). Or as Adams et al. (2017) state it: the next step is to create a framework for applying circular economy to buildings overcoming key economic, technical and organizational challenges.

To retain value and make upcycling possible a building should be deconstructed, which means: dismantling buildings with the goal of maximizing the reuse potential of its components (CIB CSIR, 2000). This deconstruction can be done at different levels, for example the levels out of Figure 1: Reuse, Remanufacture and Recycle. Disposal is left out because it is linked to demolishing instead of deconstructing. These levels can function as strategies for the deconstruction of a building. The goal of the research is to analyse the most important

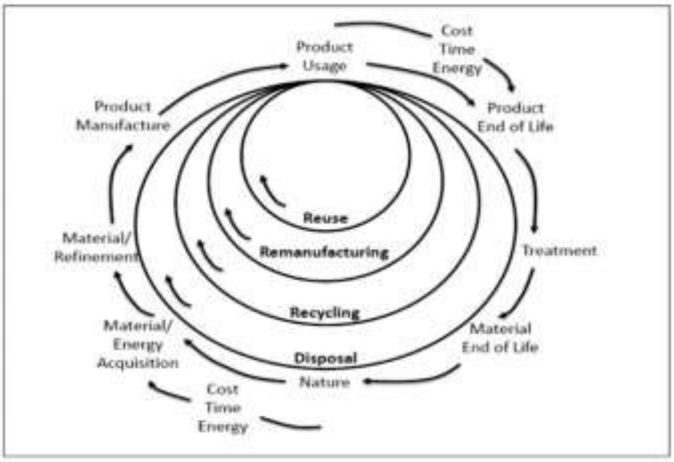

Figure 1 Product life cycles (Korhonen et al., 2018)

preconditions per value retaining deconstruction strategy (DS).

This paper is structured as follows. At first a theoretical framework is established on value retaining deconstruction strategies and their preconditions. In the subsequent section the methodology is explained, which includes a multiple case study. The results are presented hereafter, which focus on the preconditions for deconstruction strategies and to which extent preconditions identified in literature match with those identified in the case studies. Conclusions will be presented in the next section, where after the paper is finished with a discussion including the limitations of the research.

2 THEORETICAL FRAMEWORK

This section presents the theoretical framework that is established through reviewing literature. The search terms: 'value retention and deconstruction strategy' and 'deconstruction strategy and precondition or barrier or enabler or requirement' where used on Scopus and Web of Science. When the start set of literature was identified, backward snowballing (Wohlin, 2014) was used to identify additional literature. This resulted in 13 papers naming different deconstruction strategies and 10 papers mentioning preconditions. The preconditions are categorized in two categories which are developed by a bottom-up approach.

2.1 Value retention

The concept of CE states that the time a resource spends in the inner circle of Figure 1 should be maximized. Materials should first be recovered for reuse, refurbishment and repair, then for remanufacturing and only later for raw material utilization, which has been the main focus in traditional recycling. According to CE, combustion for energy should be the second to last option while landfill disposal is the final option. In this way, the product value chain and life cycle retain the highest possible value and quality as long as possible and is also as energy efficient as it can be (Korhonen et al., 2018). So, value is retained as long as possible. Zink & Geyer (2017) support these product life cycles: "The core of CE refers to three activities: reuse at the product level (such as "repair" or "refurbishment"); reuse at the component level (e.g., "remanufacturing"); and reuse at the material level ("recycling"). These different concepts are still broad, but could be the basis for deconstruction. These concepts also have potential in a financial way. Because, once a raw material is extracted, refined and produced with the usual costs, it makes economic and business sense to use the value produced as long as possible (Asif, Lieder & Rashid, 2016; Rashid, Asif, Krajnik & Nicolescu, 2013; Mihelcic, 2003). In addition to this Korhonen et al. (2018) state it is best to recycle products as high value products instead of as raw materials, so the economic value of the product is contained. This is because the value embedded in materials is used many times (kept in the economic circulation as long as possible) instead of only once, as is usually the case in the modern global economic system (Korhonen et al., 2018).

2.2 Deconstruction strategies

Deconstruction is the process of dismantling a building in order to salvage its materials for recycle or reuse, also known as "construction in reverse" (Cruz Rios, Chong, & Grau, 2015). Literature provides a lot of deconstruction strategies with different levels of detail and different approaches. In this research, all identified strategies are summed up and then a first analysis step is taken by shortening the list so only DS that appear 5 times or more often remain. The result of this analysis is visible in Table 1. After sorting the strategies on importance, they are organized by value retention in Table 2.

Among the seven selected deconstruction strategies, only three are selected for this study to retain only the deconstruction strategies which apply

Table 1 Deconstruction Strategies

Strategy	Number of appearances	Literature
Recycle	10	(Akbarnezhad, Ong & Chandra, 2014; Alba Concepts, 2018; CIB CSIR, 2000; Cramer, 2009; Ellen MacArthur Foundation, 2013; Kircherr, Reike & Hekkert 2017; Korhonen et al., 2018; Lansink, 1980; Parto, Loorback, Lansink & Kemp, 2007; Potting, Hekkert, Worrell & Hanemaaijer, 2017)
Reuse	9	(Akbarnezhad et al., 2014; CIB CSIR, 2000; Cramer, 2009; Ellen MacArthurFoundation, 2013; Kircherr et al., 2017; Korhonen et al., 2018; Lansink, 1980; Parto et al., 2007; Potting et al., 2017)
Recover	6	(CIB CSIR, 2000; CIB CSIR, 2000b; Cramer, 2009; Lansink, 1980, Parto et al., 2007; Potting et al., 2017)
Disposal	5	(CSIR CIB, 2000; CSIR CIB, 2000b; Cramer, 2009; Korhonen et al., 2018; Lansink, 1980; Parto et al., 2007)
Reduce	5	(CSIR CIB, 2000; Cramer, 2009; Kircherr et al., 2017; Parto et al., 2007; Potting et al., 2017)
Refuse	5	(CSIR CIB, 2000b; Cramer, 2009; Lansink, 1980; Parto et al., 2007; Potting et al., 2017)
Remanufacture	5	(Alba Concepts, 2018; Cramer, 2009; Ellen MacArthurFoundation, 2013; Korhonen et al., 2018; Potting et al., 2017)

to buildings in end-of-life stage. Both categories 'refuse' and 'reduce' focus on the prevention of deconstruction, while this paper aims to look into the value retention possibilities when deconstruction is

necessary. Therefore, both categories are removed from the list. 'Recover' and 'disposal' both do not retain value, so should be excluded. These strategies do not focus on the retention of value, so are beyond the scope of this research. This results in a final list of three deconstruction strategies shown in Table 3, which is sorted on amount of value retention. Reuse means an object is used again either for its original purpose or for a familiar purpose, without significantly altering the physical form of it (Van den Berg et al., 2019a). An important characteristic of this strategy is that the product does hardly need any adaptions and no repair or refurbishment (Reike, Vermeulen & Witjes, 2018). Reuse of building components, preserves the invested embodied energy of the deconstructed building components by re-using

Table 2 Deconstruction strategies end-of-life

Order of value retention	Deconstruction strategy
1.	Refuse
2.	Reduce
3.	Reuse
4.	Remanufacture
5.	Recycle
6.	Recover
7.	Disposal

them and extending their service life. It reduces cost, energy use and carbon emissions because there is no process for recycling or transportation to a landfill needed (Akbarnezhad et al., 2014). Therefore, object reuse is the most preferred strategy from a material efficiency perspective, when buildings have to be demolished (Van den Berg et al., 2019a).

Remanufacturing applies where the full structure of a multi-component product is disassembled, checked, cleaned and when necessary replaced or repaired in an industrial process (Reike et al., 2018). Remanufacturing aims to restore a product to its original manufacturer's specification from a quality, performance and warranty perspective (Sitcharangsie, Ijomah, & Wong, 2019). But expectations are tempered a little because recycled components are used in the product (Reike et al., 2018). In other words, remanufacturing is about product life extension by retaining a product at the highest possible value for the longest possible time (Jensen, Prendeville, Bocken, & Peck, 2019).

Recycling is reprocessing recovered objects with a manufacturing process and making it into a (component for a) final object again (Kibert, 2016). It means processing of mixed streams of both products

Table 3 Deconstruction strategies (value retaining order)

Order of value retention	Deconstruction strategy
1.	Reuse
2.	Remanufacture
3.	Recycle

and waste streams by using technological equipment (Yan & Feng, 2014), including shredding, melting and other processes to capture (nearly) pure materials (Graedel et al., 2011). Recycling reduces the demand for new resources by making use of waste that would be otherwise lost to the landfill sites (Akbarnezhad et al., 2014). An often-occurring problem with recycling is that it typically reduces the object's quality, potential for future uses and economic value, which is called downcycling (Chini, 2007). Concrete objects, for example, become secondary aggregates and solid timber may be reduced to particle boards (Van den Berg et al., 2019a).

The positive effects of the deconstruction strategies are mentionded in terms of value retention. Two main parts of value retention are: "resource retention" and "the lowest possible use of energy". In Table 4 these relations are shown, scoring from + (high) to - (low). A high score means a minimal amount of resources or energy is needed to produce a new component.

Table 4 Value retention per deconstruction strategy

	Reuse	Remanufacture	Recycle
Resources	+	+	+-
Energy	+	+-	-

2.3 Preconditions for value retention

Based on the review of existing literature, 23 preconditions are identified. To eliminate duplications and similar preconditions, 9 main preconditions where established. These 9 together cover all identified preconditions. For a clear overview, the 9 main preconditions are classified in two categories: deconstruction process and deconstruction products. Table 5 gives the overall preconditions for value retention. The detailed explanation is given below.

2.3.1 Deconstruction process preconditions

To execute a value retaining strategy a building should not be complex (Adams et al., 2017). A modular way of construction makes a building suitable for reusing or remanufacturing materials (Van den Berg et al., 2019b). Components with a high functional quality have the highest potential, because they can be reused (Geldermans, 2016). But this functionality has to be documented. An enormous amount of information is necessary to properly deconstruct a building (Akbarnezhad et al., 2014). The most favourable way is when the information is already documented in the construction phase, so it can be used in the deconstruction phase (Van den Berg et al., 2019a). This information can be about material routings, recovery rates (Sitcharangsie et al., 2019), supply options or best practices (Adams et al., 2017). Proper, economical feasible, deconstruction techniques have to be available for deconstruction companies to execute value retaining deconstruction strategies (CIB CSIR, 2000; Van den Berg et al., 2019a; TNO, 2015; Adams et al., 2017). Besides the economic aspects, time is very important. Deconstruction strategies should require a minimal additional time and be stable (CIB CSIR, 2000; Sitcharangsie et al., 2019). Next to economical and time aspects, the deconstruction company has to be able to control the performance until integration in a new building (Van den Berg et al., 2019a). A minimized number of easy accessible connections (Van den Berg et al., 2019b), which are preferable mechanical, make sure materials can be deconstructed. The deployment of a storage facility might help the deconstruction company with storing the deconstructed materials (Van den Berg et al., 2019a). Standardization of components, in both dimensions and composition, is an important precondition because this improves reusability of a material (TNO, 2013; TNO, 2015).

2.3.2 Deconstruction products preconditions

When looking at material level, no toxic materials should be present. When materials have a sustainable origin, are consistent with the technological of biological cycle, they are technically suitable for value retention (Geldermans, 2016). Where a composition of fewer different materials is better (TNO, 2015). A market mechanism for recovery of materials should be present, which can be a financial incentive to use secondary materials. By balancing the returned material and the demand the financial incentive can be created (Sitcharangsie et al., 2019). Transparency in the market thereforee is important, especially about the supply and demand of second hand materials (TNO, 2015). Companies might publish their future object needs (Van den Berg et al., 2019a), so a certainty in the timing and quantity of demanded materials can be recorded (Sitcharangsie et

Table 5 Preconditions for value retention

Category	Main preconditions	Preconditions			
1. Deconstruction process	1.1 Building sequence information is archived to share with future demolition contractor	Building sequence information is archived to share with future demolition contractor [4]			
	1.2 Deconstruction techniques do not take additional time and are feasible	Dismantling of buildings should require minimal additional time [1]	Demolition contractor distinguishes appropriate routines to disassemble the building [1, 2, 4]	Demolition contractor can control the performance until integration in a new building [4]	Techniques for fast and economical attractive deconstruction are available [6]
	1.3 Certainty on deconstruction time and recovery rate	Certainty of deconstruction time [5]	Recovery rate of objects is known [5]		
	1.4 Objects are relatively easy to deconstruct	The use of reversible building connections [3]	Mechanical rather than chemical connections [4]	Minimized number of connections [3]	Good accesibility of materials [3]
	1.5 Storage facility is available	Storage facility is available [4]			
	1.6 Elements with standardized dimensions	Elements with standardized dimensions [6, 9]			
2. Deconstruction products	2.1 Material is of high quality	Non-toxic material 8	Consistent with technical or biological cycle or reusable 8		
	2.2 Second hand materials are demanded	Market for second hand materials [2, 4, 6]	Object needs for projects in the near future are clear [4, 6]	Disposal costs for demolition waste are high [1]	
	2.3 Financial case is clear and profitable	Demolition contractor identifies an economic demand [4]	Clear financial case [2]	Value of material/product is clear [2]	Recovered materials are of high value [2]

[1] (CIB CSIR, 2000) [2] (Adams et al., 2017) [3](Van den Berg et al., 2019a) [4](Van den Berg et al., 2019a) [5] (Sitcharangsie et al., 2019) [6] (TNO, 2015) [7](Akbarnezhad et al., 2014) [8] (Geldermans, 2016) [9] (TNO, 2013)

al., 2019). The development of high value secondary markets stimulates value retaining deconstruction strategies (Adams et al., 2017; TNO, 2015). This helps establishing a clear business case with an economic benefit, which is an important precondition for executing a deconstruction strategy (Adams et al., 2017). Closing, it is important this economic benefit is identified by the (de)construction company (CIB CSIR, 2000; Adams et al., 2017; Van den Berg et al., 2019a).

3 METHODOLOGY

This study is both qualitative and exploratory, focusing on the preconditions that apply when executing different deconstruction strategies. By reviewing literature in the field of construction waste management and circularity in deconstruction processes a framework combining deconstruction strategies and their preconditions is established. Three case studies are used to validate and modify this framework, so it matches with real life situations. This approach is chosen to create a holistic understanding of the present preconditions and create a generalizable context (Yin, 1994). Another reason to use the case study approach is that one cannot manipulate and control conditions and therefore the framework can be validated (Voordijk, de Haan, & Joosten, 2000).

3.1 Data collection

The data is gathered by conducting semi structured interviews at the projects, the questions are shown at Appendix I. The interviews were recorded and transcribed into text for analysis. This means interviews with the work preparer of the construction company and the project leader of the demolishing company are conducted. A big part of the semi structured interviews consisted of validating the framework that was established. Binary questions were used to validate the preconditions out of the framework, so it became clear if a precondition was present or not. Hereafter in depth questions were asked about the answers, to make clear why preconditions were or were not present. Data was also collected by going through project documentation, hereby the focus was on the building method of the building, time schedules, financial information, pictures during deconstruction and the agreements between contractor and client. To get a better understanding of the cases, all project sites were visited and a tour with the work preparer has been made during the visits.

3.1.1. Object properties

The object properties are described by making use of the Brand layers, shown in Figure 2. Only the layers: site, structure, skin and space plan are considered in this study, because they are under direct influence of the contractor. The information about different type of materials that are used in the building and how they are connected are also collected.

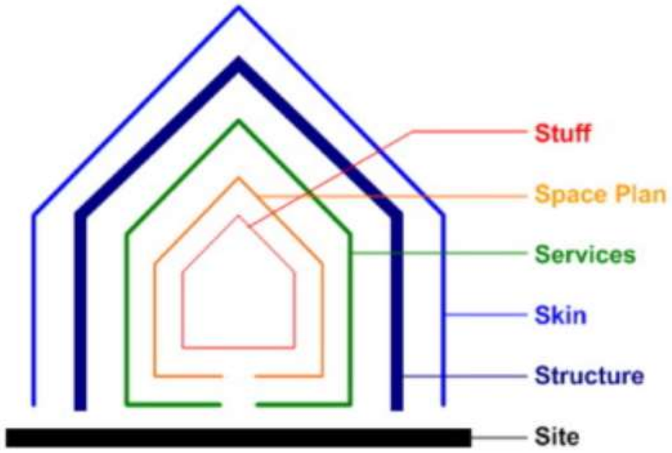

Figure 2 Brand Layers (Brand, 1994)

3.1.2 Deconstruction process

The deconstruction process research is mainly conducted by looking into time schedules and subsequently discussing these with the interviewees. Every material was discussed separately to identify the method and process of deconstruction. Special attention was spent on the main preconditions mentioned in Table 5 at the row "deconstruction process" by asking questions that are operationalized out of the 6 main preconditions. The building sequence is based on drawings. The additional time of deconstruction is researched by looking into deconstruction routines and techniques. The certainty in timing of these routines and techniques is researched to determine the certainty on recovery time and rate. The ability of easy deconstruction is researched by looking into type of connections, number of connections and their accessibility. The presence of storage place and the possible standard dimensions of materials were also observed.

3.1.3 Deconstruction products

The quality of material is assessed by checking if any toxic material is present and by looking into the consistency with the technical or biological cycle, as mentioned in the butterfly model of the Ellen MacArthur Foundation. To reuse the material as a whole is an option in the technical cycle. The second hand demand is determined by assessing if a market is present, the need for the object is clear and if disposal costs are high. The costs for deconstruction are for 80% determined by labour and equipment costs (Zahir, 2015). So the labour and equipment costs were investigated. Besides this, salvage value or waste costs was researched because this is linked to the topic of value retention. All the costs for the deconstruction or demolition scenario that was actually executed at the project are found in the project documentation. As only one of the two scenarios was executed, the other is estimated. The assumption of Braakman (2019) is used to determine the deconstruction or demolishing costs. The assumption is: deconstruction for reuse takes 95% of the original construction time, while for remanufacturing it takes 75% and for recycling 15%. So deconstruction for reuse takes 6 times as long as deconstruction for recycle, which is demolishing. This information is used to calculate the costs for the other, not executed, deconstruction strategy. The salvage value is determined by looking up the materials at several websites for second hand materials. An average of the price was taken to determine the price used for calculations.

3.2 Data analysis

The analysis was done by comparing the established framework with the preconditions mentioned by the respondents. The established framework is validated by executing case studies, thus the theory is coupled to real-life situations. The content analysis method is used to classify the categories of information (Wilson, 2011). Besides this, documents were analysed to determine which precondition were present at the case objects.

3.2.1 Deconstruction process

The deconstruction process is analysed by using the main preconditions that are present in Table 5. Therefore, the process of demolishing or deconstructing is described and attention is given to the preconditions: building information, deconstruction time, recovery rates, reversible connections, storage facility and standard dimensions.

3.2.2. Deconstruction products

The deconstruction products are described by using the main preconditions that are present in Table 5. Therefore, special attention is given to the preconditions: material quality, demand for products and the financial case.

3.3 Case objects

Two main criteria were used to select the cases. The projects should (currently or very recent) be in realisation phase, so people working on the project can be interviewed and the researcher can visit the project site. Besides this, the projects include an existing building which is at end-of-life stage. Hesselink Koffie, Cruquius Sigma and Ricardo Residences are chosen as case objects and are further clarified in Table 6. The detailed case description is shown in Appendix II. Only the building components that belong to the categories: structure, skin and space plan are taken into account. Other categories are excluded because they are not under direct influence of the construction company.

Table 6 Case objects

Project	Description
Hesselink Koffie - Winterswijk	**Goal:** Build a new hall between two existing production halls and an internal renovation. **Client:** Hesselink Koffie **Budget:** €1.200.000 **Demolishing budget:** N.A. **Size:** 3.000 m^2 existing & 400 m^2 new (1 floor) **Age:** 30 years
Cruquius Sigma – Amsterdam	**Goal:** Transform and renovate an old production hall to both houses and commercial area. **Client:** Amvest **Budget:** €18.500.000 **Demolishing budget:** €65.000 **Size:** 3.750 m^2 (4 floors) **Age:** 100 years
Ricardo Residences – Amsterdam	**Goal:** Transform an office building to 365 houses. **Client:** SAREF **Budget:** €44.500.000 **Demolishing budget:** €1.500.000 **Size:** 40.000 m^2 (12 floors) **Age:** 15 years

4 RESULTS

The two categories: “deconstruction process and deconstruction products” together form the set of 9 main preconditions, which are given in Table 5. The results in this section describe which preconditions are present in the three case studies.

4.1 Case 1: Hesselink Koffie

Hesselink Koffie is an ambitious company that devotes great care to sustainable solutions. For this reason, the client strives for a BREEAM In-Use certification for the new hall. So, the client is intrinsically motivated to retain value of the existing building and contractually recorded this by making sure two window frames of the to be deconstructed façade would be reused. All other value retaining actions were initiated during the construction phase. These changes during the construction phase were possible because of the good and long-term relation between client and construction company. They consist of a combined office and production hall in the one hall and a storage facility in the second hall. Both halls are about 30 years old. The task is to build a hall between the two, to connect them. The function of this new hall will be to house the distribution and make it possible to load the trucks at a roofed place. A visualisation can be seen in Figure 3.

4.1.1 Object properties

Site: The building is constructed on a concrete foundation, which will stay in place because the building will be expanded and therefore only gains additional foundation.

Structure: The structure consists of a ground floor of

Figure 3 Hesselink current and new situation

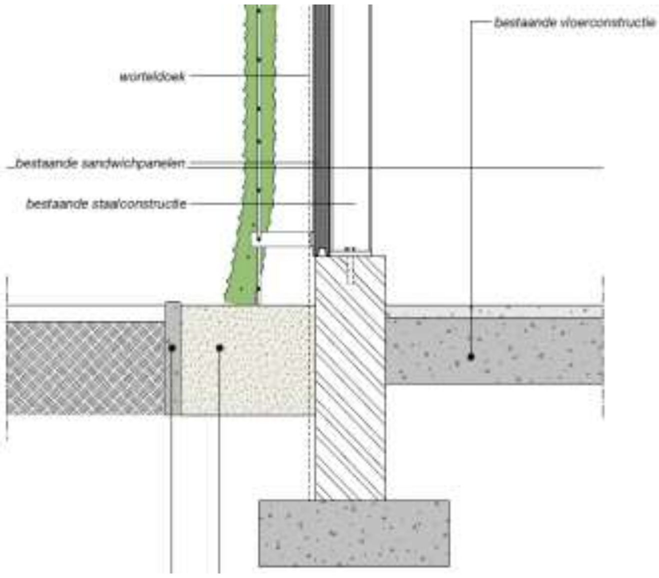

Figure 4 Detail of floor - wall connection

reinforced concrete that is placed on sand. The further structure consists of a steel frame of columns and beams. The roof is made out of sandwich panels, which consist of two layers of steel with insulation in-between. The panels are attached to the steel structure with bolts. A visualisation of the structure is given at Figure 4.

Skin: Steel columns are placed to attach the façade and the roof, which both exist of steel sandwich panels. Both the steel structure itself and the sandwich panels are connected with bolts, which form a mechanical connection.

Space plan: The production hall does not contain any interior. All the interior objects that are present in the building, are used for the office spaces and stay in place.

4.1.2 Deconstruction process

Some drawings of the initial construction of the building are present at the municipality. These drawings only describe the overview and do not include any details about connections between materials. Which means precondition 1.1 (building information) is partly present in this case, because only part of the drawings is available.

The following paragraph is about precondition 1.2 (deconstruction time). Deconstruction of the panels did take more time than demolishing them, this is because deconstruction is manual work while demolishing can be done by an excavator. When working with sensitive objects, as for example sandwich panels one has to be careful to not damage the objects. This makes the deconstruction more time-intensive and therefore more expensive, which will be made clear at the economic effects.

During deconstruction the site of the building stays in place and is extended for the newly built hall. The main part of the structure remains intact. Except for steel columns, which are placed at the spots of the new passages. By remain the main part intact, the variance in deconstruction time and recovery rate is decreased (precondition 1.3 certainty on deconstruction time and rate).

The earlier mentioned steel columns are connected by bolts and therefore deconstructed. The sandwich panels attached to the columns are deconstructed by the subcontractor specialized in facades. This subcontractor reused the panels for filling up the façade were the old entrance of the building was located. Besides the columns, the window frames could be deconstructed relatively easy because they were placed in an inner wall. For this reason, they were attached used less connections than in a façade wall. Also, a wall out of OSB panels that had to be put up during the construction phase is reused as inner wall, instead of constructing it of new gypsum. Because the wall was only a couple of months old and attached using screws it was relatively easy to reuse. This means precondition 1.4 (easy to deconstruct) is met at all objects that are deconstructed, because of their mechanical connections.

Precondition 1.5 (storage) is certainly met in this case. The reuse in the case was possible because storage space was available at the construction site. Materials could be stored both inside the building as outside on the building site. Both the sandwich panels and the window frames were stored at the construction site, the window frames were even stored inside the building.

Reusing the old panels was beneficial because they had the exact same profile, colour and (standard) dimensions. A disadvantage of using new panels will be the difference in colour and often low availability of panels with exactly the same profile. Window frames out of the old façade were also deconstructed and replaced in the new inner walls. Because the window frames were reused in an inner wall there are no problems regarding insulation value or dimensions. So, elements with standardized dimensions are sure present in this case, which means precondition 1.6 (standard dimensions) is met.

4.1.3 Deconstruction products

Only the sandwich panels contain toxic material, which is chemical waste when tossed away. All other reused materials do not contain such material. Because the materials are reused, it means they went through the technical cycle and therefore precondition 2.1 (high quality) is met. But a sidenote has to be placed, because the object does contain toxic material.

As mentioned in the previous paragraph storage is an important aspect that influences costs. At this construction site there was plenty of room for storing materials, so no costs had to be made for external storage. Storage can be necessary for two kinds of reasons. When selling materials storage is needed because supply and demand have to be matched, it might take some time for this to happen. When reusing materials at the same construction site it is because deconstruction has to be carried out before the construction works. In this project the façade panels had to be deconstructed. Hereafter the new steel structure was placed, where after the façade panels were placed back. The panels were placed back, so a demand for the panels exists. This means precondition 2.2 (second hand materials demanded) is met.

Precondition 2.3 (financial case) is met at this case because deconstruction is cheaper and even delivers money because of the sandwich panels. Their salvage value is higher than the deconstruction costs, which implies a profit. The sandwich panels at the front side of the building also stayed in place. This method was estimated to be cheaper by the construction company because less time would be needed because of not demolishing the façade. Another reason is that less material has to be purchased, because the existing façade already had enough insulation in it. The costs exist of applying the wooden frame in front of the façade. Afterwards some additional costs arose because the façade appeared to be not as straight as assumed upfront. For this reason, a worker had to construct a sub-frame on the façade, before the applying the wooden frame.

The window frames and sandwich panels belong to the skin layer, which together form around 80% of deconstruction costs and salvage value. For this reason, the skin layer is of big influence in this case study. As can be seen in Table 7 the deconstruction scenario even has negative costs, which is possible because the deconstruction costs are lower than the salvage value.

Table 7 Costs and benefits of case 1 Hesselink Koffie

	Wage costs Decon	Salvage value Decon	Waste Decon	Total Decon	Wage costs Demol	Salvage value Demol	Waste Demol	Total Demol
Structure	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Skin	€ 4.180	€ 5.984	€ -	€ -1.804	€ 660	€ -	€ 4.964	€ 5.624
Space plan	€ 1.197	€ 560	€ -	€ 637	€ 189	€ -	€ 212	€ 401
Total	€ 5.377	€ 6.544	€ -	€ -1.167	€ 849	€ -	€ 5.176	€ 6.025

4.2 Case 2: Cruquius Sigma

Cruquius Sigma is part of the bigger project Cruquius, which is located at Cruquiuseiland in Amsterdam. The whole island is transformed from an industrial area to a residential area. The client is a big pension fund that is specialized in area development. Cruquius Sigma consists of building A & B of the total 6 buildings in the Cruquius project. Building A is a monument and building B a production facility out of 1920. A visualisation of both the current and future situation of the building is given at Figure 5. There are no specific demands regarding value retention by both the client or the municipality of

Figure 5 Cruquius current and new situation

Amsterdam. However, the municipality does have one demand regarding the window frames of the monument, they should be the exact same profile and look exactly the same as the current situation is.

4.2.1 Object properties

Site: The building is constructed on a concrete foundation, which is placed on top of wooden foundation piles. A detail is shown at Figure 6.

Structure: The structure exists of reinforced concrete columns, which connects the floors of reinforced concrete to each other. The connection between column and floor is made by in-situ poured concrete.

Skin: The structure is linked by steel wall ties to the masonry façade. The façade contains steel window frames, which are connected by cement which is a chemical connection.

Space plan: The space plan contains of masonry walls with steel and wood door frames in it. The door frames still have their original height, which is why they do not match current legislation.

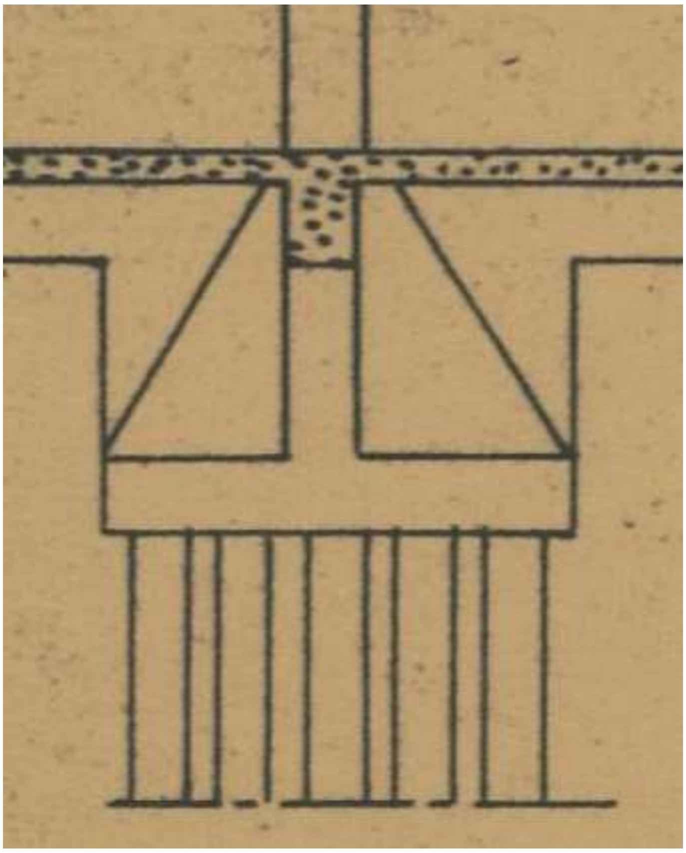

Figure 6 Foundation detail

4.2.2 Deconstruction process

Overview drawings of the building were available, which show the building has a foundation of wooden piles. The drawings also show the structure of the building, which is also visible in the building itself. Normally the dimensions of drawings might help the deconstruction company, but in this case, there was too much difference between the dimensions at the drawings and the dimensions of the building as built. The site and structure of the building are not adapted. This saves time because less deconstruction or demolition has to take place. On the other hand, additional costs arise because objects linking to the structure should be custom made. This is because the dimensions are slightly different at different places in the building. Therefore, precondition 1.1 (building information) is partly met. Some drawings are available, but because of the disagreement with reality they are not very helpful.

The total skin and space plan are removed except for the steel window frames and the door frames at the 2nd floor. The door frames are kept in place because the construction company organized its office for the project at this floor. Floor tiles and inner walls from case project 3 were used to further furnish the space. The steel window frames were not removed because the municipality demands to retain the façade image exactly the same. Since new window frames of this particular profile are not on the market the current ones are renovated and reused. The deconstruction company could not upfront estimate the time frame for deconstructing the window frames, but was sure it would be longer than in case of demolishing. Therefore preconditions 1.2 (deconstruction time) & 1.3 (certainty on deconstruction time and rate) are not met in this case.

The deconstruction of this window frames took a lot of time because they were not mounted with reversible connections. Fixation was done with glue combined with screws, which became so old and rusted that they are no longer a reversible connection. So, the objects were not easy to deconstruct and therefore precondition 1.4 (easy to deconstruct) was not met.

The window frames were not stored at the construction site, but directly sent to the renovation company. After renovation they are shipped back to the building site and placed back in the building. So precondition 1.5 (storage) is met, because storage was arranged at the renovation company.

The structure of the building should have fixed bay-dimensions. But in practice it turned out there were several centimetres of difference between different bays, so precondition 1.6 (standard dimensions) is not met.

4.2.3 Deconstruction products

Asbestos is present at the building, among others in the putty that holds the glass of the window frames. Before deconstruction, the asbestos was removed by the deconstruction company. Because of the asbestos, that was especially present in the reused objects (window frames), precondition 2.1 (high quality) is not met.

The only products in this case study with a real salvage value are the steel window frames. The demand for the window frames is at the project itself and therefore precondition 2.2 (second hand materials demanded) is met.

Precondition 2.3 (financial case) is not met, as can be seen in Table 8. Deconstruction in this case is way more expensive than demolition. This is due to the large extra amount of time it takes to deconstruct and the relatively low salvage value of the window frames. In this case the demolition strategy is used, because the fictive deconstruction costs are way higher. Except for the window frames, which are renovated. The reason for renovation is the lack of similar window frames at the market.

In this case the concrete structure is kept in place because there was a financial benefit. Keeping the construction saves money because no new materials have to be bought and also for a shorter construction time. A disadvantage is the dimension of the existing structure, all bay dimensions are slightly different. So, everything that is attached to the structure should be custom made and there is no standard in those dimensions. This takes more time because of measuring and also brings the risk of objects not exactly fitting in the current concrete structure. Then there is an additional risk because of retaining the concrete structure, because it is on wooden piles which have to be kept wet by the groundwater. Because of constructing another building next to this project, a building pit surrounded by dam walls is installed. Normally the company would use drainage to keep the building pit dry, but at this project retour drainage was also needed to keep the foundation piles wet. The costs are not included in Figure 8 because the materials were not demolished or deconstructed.

The only products in this case study with a real salvage value are the steel window frames. As can be seen in Table 8 deconstruction in this case is way more expensive than demolition. This is due to the large extra amount of time it takes to deconstruct and the relatively low salvage value of the window frames. In this case the demolition strategy is used, because the fictive deconstruction costs are way higher.

Table 8 Costs and benefits of case 2 Cruquius Sigma

	Wage costs Decon	Salvage value Decon	Waste Decon	Total Decon	Wage costs Demol	Salvage value Demol	Waste Demol	Total Demol
Structure	€ -	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Skin	€ 205.833	€ 18.798	€ -	€ 187.035	€ 32.500	€ -	€ -3.463	€ 29.037
Space plan	€ 205.833	€ -	€ -	€ 205.833	€ 32.500	€ -	€ -	€ 32.500
Total	€ 411.667	€ 18.798	€ -	€ 392.869	€ 65.000	€ -	€ -3.463	€ 61.537

4.3 Case 3: Ricardo Residences

Ricardo Residences is a transformation project of a 40.000m^2 office building to 365 apartments. The client is the real estate department of a big pension fund. This project is unique because the building is only fifteen years old and it is already being transformed from offices to houses. Another unique aspect of the project is that great amount of time the deconstruction company has. They already started in August, while the construction company just started in February. While the project was originally outsourced as a demolishing project, the deconstruction contractor used the big amount of time to deconstruct the building.

4.3.1 Object properties

Site: The building is constructed on a concrete foundation that is built on bored concrete piles. The foundation and the piles are connected to each other by pouring concrete filled with iron rebar.

Structure: The coupling between foundation and structure is done by applying iron pins in both parts and securing them with concrete, which can be seen at Figure 7. This connection is used at both the prefab and the in-situ concrete. Because all materials are attached to each other using concrete there is no potential for deconstruction. The structure exists of prefab walls, prefab columns and prefab floors, which are both wide slab floors and hollow core floors. The floors always lay on a thickening in the wall. There are two different options, or they lay without connection, or they are fixated with an iron pin and concrete. For the hollow core floors, only the joints between two plates are filled with concrete. While the wide slab floors are topped up with concrete in total, so they become one big concrete plate. Additionally, a concrete layer is sometimes added on top of the hollow core floors, for constructive safety.

Skin: The concrete columns in the structure hold the aluminium curtain wall, which is part of the skin, using consoles. The consoles are applied by bolts, which is a reversible connection and therefore is potentially suitable for deconstruction. Other parts of the façade consist of masonry which is connected

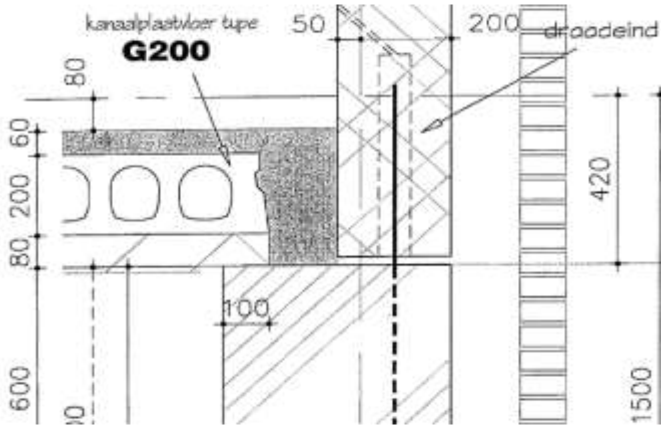

Figure 7 Connection between wall and floor

with galvanized wall ties to the concrete structure. Masonry exist of stones connected by cement, in which the ties are placed also, so a non-reversible connection.

Space plan: The space plan incorporates the inner part of the building. At this project the floor tiles were not glued to the floor, so they could easily be deconstructed. Another benefit was the tiles were placed under the inner walls and not between them. Therefore, all the floor tiles still had their standard dimensions. The only loss of quality to the floor tiles is because the profiles for the inner walls are bolted through the floor tiles to the concrete floor. These can easily be deconstructed. An additional reason for easy deconstruction is the low age of the building and the fact all materials are inside the building. This lowers wear by weather circumstances or time.

The ceilings are also part of the space plan. Because it are system ceilings they could easily be deconstructed. The ceiling plates lie loosely on the aluminium frame. This frame is attached to the floor above by iron bars which are chemically connected. So the bars cannot be taken out, but the bars can be disconnected from the aluminium frame.

4.3.2 Deconstruction process

Precondition 1.1 (building information) is met because a lot of information was available about this building, including the total set of drawings. The reason for all drawings being present is the relatively young age of the building. The drawings helped the deconstruction company to calculate amounts of materials to be sold.

The schedule shows a total of 345 planned days for the deconstruction company, of which 165 contain only demolishing activities. So, 50% of the time the deconstruction company was deconstructing and the other half of the time they were demolishing. According to Braakman (2019) deconstruction for reuse takes 95% of the original construction time, while for remanufacturing it takes 75% and for recycling 15%. So deconstruction for reuse takes 6 times as long as deconstruction for recycle, which is demolishing. Therefore, the deconstruction of the objects would have taken (165 / 6) 28 instead of 165 days when demolishing the whole building. So deconstruction definitely takes more time, which makes sure precondition 1.2 (deconstruction time) is not met. At the same time, the deconstruction contractor made a schedule and worked according the schedule. Next to the schedule focussed on time, an overview of the to be deconstructed and sold materials was established. This implies precondition 1.3 (certainty on deconstruction time and rate) is met. The site and structure of this building totally stayed in place. Except for the top two floors, which are removed from the building. The skin is also removed at the two top floors and undergoes some adaptions because balconies are. The space plan is totally deconstructed, at all floors. So, all concrete elements of the structure stayed in place, except for the ones at the two top floors. The same situation applies to the masonry with insulation and the inner walls of sand limestone. These were all demolished because both the concrete as the masonry are not elements that can be deconstructed. The insulation material was deconstructed, because this is attached to the masonry by a mechanical connection. Further the cement bonded fibreboard plates and aluminium curtain wall are deconstructed because they are attached using mechanical connections. The space plan of the building consists of three main objects: floor tiles, systems walls and a system ceiling. Which are all three deconstructed. Two steel stairs were at the top floor, which are also deconstructed because of their high value and mechanical connection. The only object out of the space plan that is demolished are the ceramic tiles that were on the walls and floors. These are glued to the underlying structure and therefore cannot be deconstructed. So a lot of materials are mechanically connected and therefore easy to deconstruct, which is precondition 1.4.

During the first part of the deconstruction phase the whole parking garage was available for the deconstruction company to store objects in. This had the benefit that materials could be stored and did not have to be covered separately. Because of this storage the materials could be transported using full trucks, which is financially beneficial. It also makes sure precondition 1.5 (storage) is met.

Precondition 1.6 (standard dimensions) is also met. This is because the floor tiles, ceiling plates, cement bonded fibreboard plate and aluminium curtain wall all have standard dimensions. These dimensions are also applied at other construction sites and by trade companies, therefore the materials were easy to sell.

Table 9 Costs and benefits of case 3 Ricardo Residences

	Wage costs Decon	Salvage value Decon	Waste Decon	Total Decon	Wage costs Demol	Salvage value Demol	Waste Demol	Total Demol
Structure	€ 349.440	€ 9.488	€ -	€ 339.953	€ 55.175	€ -	€ -1.870	€ 53.305
Skin	€ 399.360	€ 101.035	€ -	€ 298.325	€ 63.057	€ -	€ 14.674	€ 77.731
Space plan	€ 915.200	€ 779.109	€ -	€ 136.091	€ 144.505	€ -	€ 439.491	€ 583.997
Total	€ 1.664.000	€ 889.631	€ -	€ 774.369	€ 262.737	€ -	€ 452.296	€ 715.032

4.3.3 Deconstruction products

No toxic materials such as asbestos are present in the building, which is because it is a newly built building. This young age also means materials are still good for selling. In general, they look well and still satisfy the trends in the market. Therefore precondition 2.1 (high quality) is met.

Precondition 2.2 (second hand material demanded) is also met. But in contrast to the other two cases, materials are sold to external projects in this case. Selling is done at an informal market, that is known to the deconstruction company. Most sales are done at a person level and are made very sudden, which means less clarity about demand in the long-term.

Precondition 2.3 (financial case) is partly met because in total deconstruction is a little more expensive, but especially on the space plan layer it is way cheaper. This because, the combined man hour costs for demolishing and deconstruction are €1.665.000. The deconstruction company worked for 260 days with 20 people on average, having an hour wage of €40. The costs and benefits for both demolishing and deconstruction are given in Table 9. As shown in the figures, the total price for deconstruction is €775.000 and the price for demolition €715.000. This means there is only a minor difference of €60.000. The space plan layer is the most important with about half of the costs for both deconstruction and demolition and by far the biggest stake of salvage value and waste costs. In this

Table 10 Presence of main preconditions per case study

Category	Main preconditions	Case 1: Hesselink Koffie	Case 2: Cruquius Sigma	Case 3: Ricardo Residences
1. Deconstruction process	1.1 Building sequence information is archived to share with future demolition contractor	Only overview drawings available.	Overview drawings available, but dimensions were not correct.	Total set of drawings available.
	1.2 Deconstruction techniques do not take additional time and are feasible	Deconstruction of all reused materials takes additional time.	Deconstructing window frames did take additional time.	Deconstruction took way more time than demolishing would have done.
	1.3 Certainty on deconstruction time and recovery rate	By keeping a big part of the building in place, uncertainty is reduced.	Deconstruction time for window frames was unclear, but found out by a pilot.	A clear schedule regarding time and to be sold materials was established.
	1.4 Objects are relatively easy to deconstruct	All deconstructed objects are connected mechanically.	No easy deconstruction because of non-reversible connections.	A lot of mechanically connected materials.
	1.5 Storage facility is available	Enough storage possibilities, both in and outside the building.	Storage present at the renovation company.	Storage was possible in the parking garage of the building
	1.6 Elements with standardized dimensions	Facade panels have standard dimensions and same colour as rest of the building.	No standard dimensions.	Floor tiles, ceiling plates, cement bonded fibreboard plate and aluminium curtain wall have standard dimensions.
2. Deconstruction products	2.1 Material is of high quality	Toxic material is present, but still this material is reused.	Asbestos in putty that holds the glass.	No asbestos present and a lot of reused objects.
	2.2 Second hand materials are demanded	Only demand at the project itself.	Window frames are demanded at the project itself.	Materials are sold to external parties
	2.3 Financial case is clear and profitable	Reusing sandwich delivers money in this case.	Demolition is way cheaper. Keeping structure intact saves construction time.	In total deconstruction is a litle more expensive, but especially on the layer space plan it is way cheaper.

Green: Precondition is met \| Yellow: Precondition is partly met \| Red: Precondition is not met

case the reason for this is the deconstruction of the space plan and keeping the structure and skin of the building intact. A remarkable fact is the zero cost and benefits of the site layer. This is because the whole site could be kept in place and therefore no adaptions were made.

4.4 Cross case analysis

This section describes similarities and distinctions of the three case study objects. The structure is linked to the main preconditions given in Table 5. An overview of the preconditions per case is given in Table 10. The table contains red, yellow and green boxes. In case of a red box the precondition is not met, yellow means the precondition is partly met and green means the precondition is completely met.

4.4.1 Deconstruction process

1.1 Building sequence information is archived to share with future demolition contractor: a lot of information was present in case 3. The construction company still possessed all drawings used for the original construction of the building. This is including all details and the technical description, so the deconstruction company knew upfront how the building was constructed. The construction company gained this information because they are closely related to the company who constructed the building initially. This was not the case at case 1 and 2. Some information was present, but this was occasional. At case 1 the client had some drawings in his possession, while at case 2 some of the original drawings where found. But this gave no total overview of the building. At case 2 the drawings were not very useful because the dimensions in reality differed by centimetres.

1.2 Deconstruction techniques do not take additional time and are feasible: Deconstruction took longer than demolition at all cases, this is because materials have to be handled more carefully and the work is manual instead of executed by machines. Deconstruction companies do not have much experience with deconstruction yet, wherefore deconstruction takes additional time.

1.3 Certainty on deconstruction time and recovery rate: Because of a lack of experience with deconstruction both deconstruction time and recovery rate are not known. Deconstruction companies continuously learn when executing the project. To increase certainty on deconstruction time a test was done at case 2. To deconstruct all metal window frames the deconstruction company first removed two, to determine the deconstruction time and extrapolate this to the other window frames. The deconstruction company at case 3 had more experience deconstructing, which resulted in a schedule both in time and in to be sold materials.

1.4 Objects are relatively easy to deconstruct: Case 2 does not contain any reversible connections. While the window frames are deconstructed, this is a very time-intensive manual job. Case 1 and 3 do include reversible and good accessible connections. At case 1 the sandwich panels, OSB panels and steel columns could easily be deconstructed because of their reversible (bolt) conne0-ction. Case 3 also includes a lot of reversible connections. The sandwich panels, fibreboards, system walls and steel stairs are all connected with bolts. While the floor tiles, insulation and acoustic panels are even connected more loosely. So, all materials that are moved are connected by a reversible connection, while some materials that are reused at the same place can also exist of a non-reversible connection.

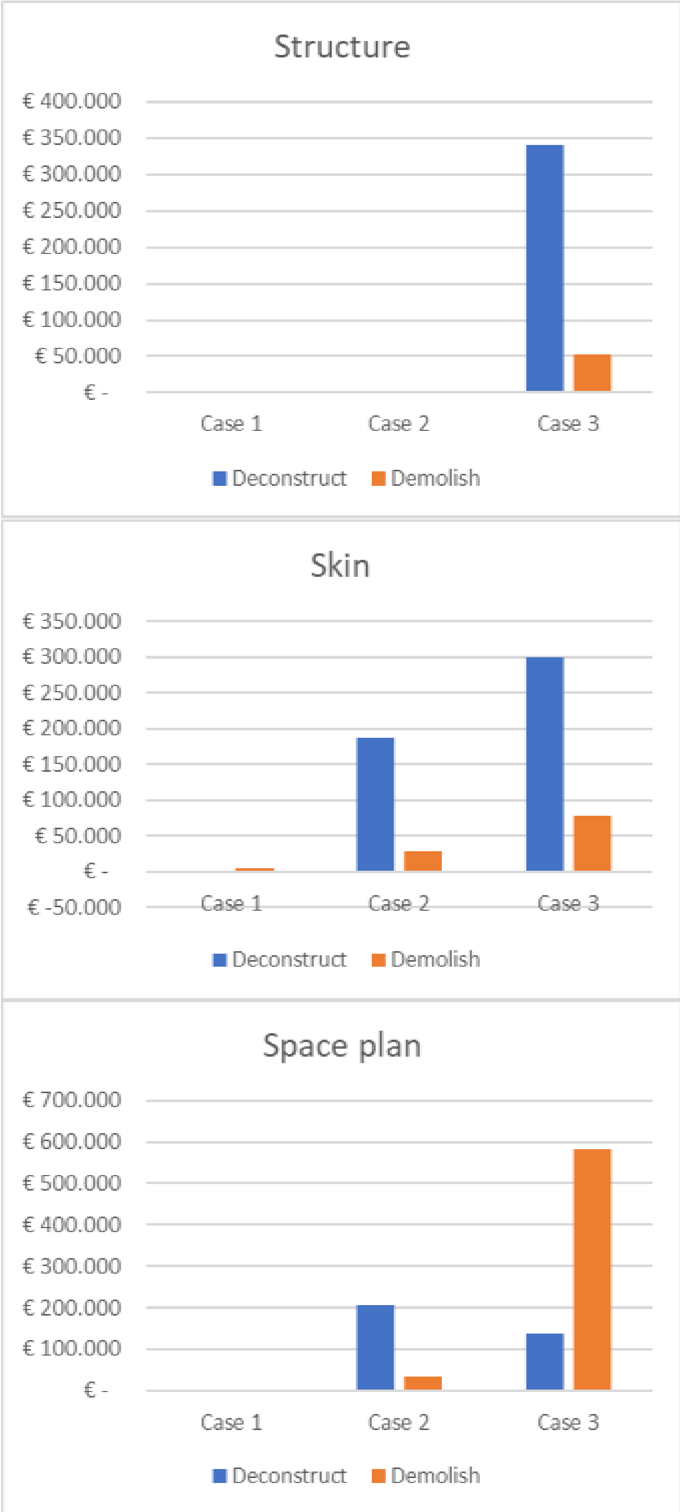

Figure 8 Cost comparison per Brand layer in three cases

1.5 Storage facility is available: Case 1 and 3 have a lot of storage facility. Case 1 because it is a production facility, including storage room for the production company. The storage space was available during the construction period. The deconstruction at case 3 started very early and therefore the parking garage under the building was available as storage facility. At case 2 there was no room for storage at the construction site, but storage was arranged at the renovation company.

1.6 Elements with standardized dimensions: Only case 1 and 3 include materials with standard dimensions, which are the floor tiles, system ceiling, system walls, sandwich panels and OSB panels. These are all materials that are deconstructed instead of demolished.

4.4.2 Deconstruction products

2.1 Material is of high quality: The structure of all three buildings was kept in place, at case 3 this means also the outer parts of the building (skin) where kept in place. This was done at case 1 by reusing some of the insulated panels, which do include toxic material (insulation material). Case 3 has by far the most reused materials and is the only case where materials out of the space plan layer are reused. Case 2 did contain toxic material, which is asbestos in the putty for the glass.

2.2 Second hand materials are demanded:
In all three cases second hand materials are demanded. But where in case 1 and 3 many different objects are demanded, at case 2 this only holds for the steel window frames. Case 1 only contains internal demand for materials, which means at the same project. Case 3 also contains a lot of external demand because all materials of the layer space plan are reused external.

2.3 Financial case is clear and profitable: The economic results of the three case studies are summarized in Figure 8, which shows the total cost for demolition and deconstruction sorted per Brand layer. Every table shows a different layer and gives the costs for both deconstruction and demolishing for all three cases. Deconstruction did not turn out to be cheaper. Except for the space plan layer in case 3, demolition is way more expensive here. The main reason is the big amount of salvage value when deconstructing in this case, which is mainly because of the system walls that are present in the building. Also, the reuse of sandwich panels at case 1 has a financially positive effect.

5 DISCUSSION

The goal of this research is to analyse the most important preconditions per value retaining deconstruction strategy. Major findings of the study show that eight of the nine preconditions, which were identified from literature, do stimulate deconstruction. This means only precondition 1.2 does not. Each individual precondition will be analysed in the next paragraph, where after the relations between preconditions will be discussed.

5.1 Preconditions for deconstruction

Precondition 1.1 (building information) states 'building sequence information has to be shared with the deconstruction company' is a precondition for deconstruction. The deconstruction company mentions the building sequence information is used to prepare the deconstruction process. This is supported by Van de Berg et al. (2019b), who also mentions the deconstruction company should be aware of the building sequence.

The information that is provided in a 'typical' building information model is enough for the model of Akbarnezhad et al. (2014) to evaluate different deconstruction strategies on cost, energy use and carbon dioxide production. But a building information model often is not present at old buildings. When looking into both literature and practice, however existing much longer, BIM is only applied at big scale since ± 10 years. This means most buildings constructed in the past 10 years have a BIM model containing information about the building, which is established by the construction company.

However, the problem is that most buildings are not deconstructed for at least 50 years, but are adapted in the meanwhile. Therefore, the BIM model does not match with the real situation anymore, when a building comes to end of life stage. The BIM model is not adapted when adapting a building, because the client does not see any value of adapting it. Therefore, he does not want to pay for it. This value is only present when looking at the long-term benefits. Thus, as long as building owners remain focusing on the short-term financial benefits, BIM models will not be kept up to date. This is in line with Guillen, Crespo, Gómez, González-Prida, Kobbacy & Sharrif (2016), who state there are very few cases where BIM has been applied in operation phase of a building. The mentioned reasons are the lack of well characterized benefits and use cases. Besides this, there is a lack of interoperability between BIM models (Shirowzhan, Sepasgozar, Edwards, Li, & Chen, 2020). Which is often related to the difficulty of data exchange, data recognition and a lack of required data (Shirowzhan et al., 2020). According to Volk, Stengel and Schultmann (2014) other challenges are: high modeling effort from captured building data into semantic BIM objects, high costs for updating on information and the handling of uncertain data, objects and relations. Because of these difficulties, the BIM model often is not updated after the construction phase.

Precondition 1.2 (deconstruction time) states deconstruction should not take more time than demolishing. This precondition is not met in any of the cases, because deconstruction always did take longer. In literature, it is stated that only a minimal amount of additional time can be used (CIB CSIR, 2000) or fast deconstruction techniques should be available (TNO, 2015). While Densley Tingley, Cooper & Cullen (2017) already found out in practice that the deconstruction time does not function as a limit in steel reuse. Their study showed that the deconstruction time is mentioned as a barrier in most commonly identified barriers, but do not recognize this in their empirical results. Identical in this research, deconstruction time is not perceived as a precondition for reusing materials and therefore not for deconstruction. This can be explained by the fact it is acceptable to increase timespan, as long as money (in terms of benefits) or quality rises. Thus, it is logical deconstruction time is no precondition, because it can be compensated by money or quality.

Precondition 1.3 (certainty on deconstruction time and rate) is at least partly found in all cases. When the time or rate was not clear, the deconstruction company did a pilot to find out the rates. This matches with Sitcharangsie et al. (2019), because they also mention the rates should be known upfront. This is because the deconstruction time and rate should be known to make an estimation of the duration and the amount of materials that will become available. Currently, this often is done by intuitive planning procedures, which end up in suboptimal plans. This can be improved by increasing the efficiency of the planning process (Sanchez, Rausch, & Haas, 2019). Therefore, Sanchez et al. (2019) confirm the necessity of information as deconstruction time and rate.

Currently these rates are hard to predict, because deconstruction companies in particular have experience with demolition, rather than deconstruction. When a paradigm shift happens from demolition to deconstruction, it is expected that deconstruction companies can make a better estimation because they will have more experience. This shift can be established by education in the deconstruction industry or governmental leadership (Sanchez et al., 2019).

Precondition 1.4 (easy to deconstruct) states objects should be easy to deconstruct. At case 1 and 3 the easy to deconstruct materials are deconstructed, while others are not. Which means the materials with a mechanical connection were deconstructed, while the materials with a chemical connection were not. Materials with a mechanical connection are easier to deconstruct, because they can be loosened from each other in a proper way (Van den Berg et al., 2019a) and therefore they improve reusability (Mignacca, Locatelli, & Velenturf, 2020).

The reason that materials in existing buildings often are not easy to deconstruct, is their traditional assembly technique. It was in 1994 that Latham introduced the modern methods of construction, which consists of modular and off-site construction (Akinade, et al., 2017). But still a lot of buildings are not designed according to these principles, which means the traditional assembly techniques keep coming back in the to be deconstructed buildings. Anastasiades, Blom, Buyle & Audenaert (2020) state it would be interesting to create a dedicated set of parameters to score an object regarding circularity of bridges, which might also be helpful for buildings. To gain insight in the circularity score of a present building.

Precondition 1.5 (storage) was present in all case studies. This means the statement of Van den Berg et al. (2019b) that storage should be available is agreed upon. This statement is also supported by Densley et al. (2017), who identified the absence of storage of recovered materials as a top 3 barrier for reusing materials and therefore deconstruction.

Storage is needed to bridge the gap in time between supply and demand, because optimal logistics does require warehouses (Hsu, Aurisicchio, & Angeloudis, 2019). This gap is the time between deconstruction and construction of the new building. It is financially beneficial to have storage at the deconstruction site, because transport to an external storage places costs additional money, which results in less change on a positive business case. Storage is a precondition because in practice it turns out the gap in time is virtually always present.

The precondition can be met by taking into account storage already before starting the deconstruction of the building, which nowadays can be done by the use of optimization models (Hsu et al., 2019). In this way, the deconstruction process can be tailored to the available storage, so no material has to be disposed. When storage at the site is not possible, external storage is an option. In this case just-in-time logistics is necessary to haul materials from the deconstruction site immediately when they are deconstructed.

Precondition 1.6 (standard dimensions) is found in case 1 and 3. All deconstructed materials have standard dimensions, but the deconstructed window frames of case 2 do not have standard dimensions. So, the use of elements with standard dimensions does stimulate deconstruction (TNO, 2015) but deconstruction is also possible without them. Deconstruction is stimulated when standard dimensions are present, because materials with standard dimensions are easier to reuse in a new building. Jaurequi (2017) agrees upon this and states that modularity reduces a product's operational costs and costs less managerial effort in the future project.

This is because it takes less time to install them (Xu, Zayed, & Niu, 2020), because no customization has to be done. Therefore, this precondition also stimulates precondition 2.2 (second hand material demanded), because materials with standard dimensions are easier to reuse.

Precondition 2.1 (high quality) is partly met in the cases. Which means material is not toxic and can be reused in the construction process. This precondition is mentioned by Geldermans (2016), as he states high quality pure material use is necessary for deconstruction. Geldermans (2016) identifies quality as functional performance. In the cases it turns out the toxic material is removed when necessary or left in place when possible, so the presence of toxic material is no barrier for deconstruction. Only the technical cycle is followed in the cases, because materials were reused in buildings. So, high quality materials stimulate deconstruction, but it is no requirement. High quality material is necessary to stimulate reuse because the balance material costs versus labor cost is very important. Complex and valuable materials have the highest change of reuse (Milios, Beqiri, Whalen, & Jelonek, 2019), because the labor costs are low compared to the material value. This ratio is important because when the labor costs are relatively high, this is the focus point of companies. In such a case the material costs will not be bothered.

Precondition 2.2 (second hand material demanded) means a demand for the material should be present (Adams et al., 2017; Van den Berg et al., 2019b). This precondition is met in all cases, with a difference in internal and external demand. Case 1 and 2 contain an internal demand, while case 3 contains an external demand. Internal means the materials are demanded at the project itself, while external means the materials are demanded at another project. This demand, either internal or external is important because, the deconstruction company will not deconstruct materials without expecting a demand for them. This is because a demand means a source of income for the deconstruction company. For this reason, "second hand material demanded" is a precondition for deconstruction. This precondition is supported by Guy (2011), who state a lack of client interest is a barrier for reuse of materials.

When looking from the perspective of this client, there is a logical explanation why a demand for second hand materials is not always present. New materials are easy to order and can be customized according to the clients wishes, while second hand materials only come in the shape and quantity as they are deconstructed. Therefore, using second hand materials limits the client's freedom of procurement and costs more time. Because of the relatively high labor costs, additionally increased by tax, these costs excel the financial benefit of using second hand materials (Milios et al. 2019). Another reason for this phenomenon is the absence of organization competences to procure second hand materials (Milios et al. 2019), because construction companies traditionally are fitted for the use of new materials.

Precondition 2.3 (financial case) means the financial case should be clear and profitable (Adams et al., 2017). This precondition was only present at case 1, where sandwich panels delivered money. At case 3 deconstruction was a little more expensive, but when taking into account the learning effects for the deconstruction company it might be profitable on the long term. Because the company can use the gained knowledge at future projects. At case 2, deconstruction was very expensive, but there was no alternative because the façade view should remain intact.

A clear financial case is important because profitability is the right to exist for every company. The problem for the reuse of materials lies in the relative high labor costs in relation to material prices (Gorgolewski & Morettin, 2009). Especially for the damage-sensitive materials it turns out new materials often are cheaper because the labor costs of repair are relatively high (Milios et al. 2019). More complex and higher value materials herefore have a higher reuse potential (Milios et al. 2019). The researched materials are not complex high value materials. When looking into buildings, the installations are the most complex high value materials, which therefore have the highest reuse potential.

Relations between preconditions occur in different ways. Precondition 1.1 (building information) influences all process preconditions and precondition 2.1 (high quality). If information about the building is present, it is used to determine deconstruction rates, techniques and material dimensions and quality. These can also be determined without the information being present, but this means it will take more time because the building has to be inventoried. Besides this, building information is not the only source to determine the other preconditions. For precondition 1.3 (certainty on deconstruction time and rate) the information and experience of a deconstruction company also is necessary.

Another relation exists between precondition 2.2 (second hand material demanded) and preconditions 1.6 (standard dimensions) and 2.1 (high quality). The presence of both preconditions 1.6 and 2.1 raise the change of precondition 2.2 being present. This is because materials of high quality and/or with standard dimensions are more popular in the market.

5.2 Scientific relevance

Previous researches have already looked into barriers or preconditions for CE, but not for deconstruction in construction sector. Barriers for moving towards a CE in waste management are identified by Mahpour (2018). In the infrastructure industry, barriers are identified by Iacovidou & Purnell (2016). So in related areas, a start with identifying barriers has been made. Iacovidou & Purnell (2016) mention it is recommended to further explore possible barriers for implementing a CE (Mangla et al., 2018; Adams et al., 2017). So preconditions or barriers for CE are identified, but preconditions for deconstruction in the construction sector have not been identified yet.

This research looks into preconditions for deconstruction in construction industry, a relative clean field. Therefore, this research contributes to the scientific knowledge about deconstruction in construction industry. Knowledge about the preconditions for deconstructing rather than demolishing is important to stimulate the deconstruction of buildings at their end-of-life, which contributes to a circular economy (Zahir, 2015). The identification of preconditions familiarises the (de)construction companies with deconstruction instead of demolishing. It helps them to make a substantiated choice for the deconstruction strategy of a building. Besides this, it helps companies to get familiar with the benefits of deconstruction and prepares the for the desired circular economy in 2050. At this moment demolition is the most preferred deconstruction strategy by deconstruction companies, which mostly depends on their experience and perception (Zahir, 2015). When taking into account the preconditions, the deconstruction company might choose a value retaining deconstruction strategy more often. Because, knowing what preconditions should be present, reduces the risk when accepting a new project (Zahir, 2015).

Van den Berg et al. (2019a) state three major preconditions: identify economic demand, distinguish disassembly routines and control future performance. Van den Berg et al. (2019a) state if one of the three preconditions mentioned in the research is not present, deconstruction will not happen. In contradiction to Van den Berg et al. (2019a) this research concludes that not all preconditions have to be present for deconstruction. Every individual main precondition, except for precondition 1.2 (deconstruction time), stimulates deconstruction, but there is no necessity for every precondition to be present. A possible explanation could be that Van den Berg et al. (2019a) looked into detail into one specific case, while this study looked into three cases at a more abstract level. The presence of three cases might cause inconsistencies in the preconditions, wherefor a precondition is not present in every project. Another possible explanation is that the case project of Van de Berg et. al. (2019a) contained a lot of deconstruction, while the cases in this research differed a lot in terms of deconstructed materials. Therefore, differences between the cases are more likely to exist.

Hart, Adams, Giesekam, Densley Tingley & Pomponi (2019) looked into barriers and enablers for a CE, specific in the built environment. The general outcome is that while a lot of technical barriers can be identified, the real issues are the cultural and financial / market issues. This conclusion is supported by this research, which looks into preconditions for deconstruction of buildings. This research also finds preconditions in a financial and market context.

6 CONCLUSION

The goal of this study is to analyse the most important preconditions per value retaining deconstruction strategy. The preconditions can be used by construction companies to assess an existing building on possibilities for deconstruction. The main preconditions for deconstruction are given in Table 11. The preconditions are established by a literature review and verified by three case studies.

Precondition 1.2 (deconstruction time) is not included as a precondition for deconstruction. Because it is acceptable to increase timespan, as long as money (in terms of benefits) or quality rises. This is supported by the case studies, where precondition 1.2 was not present but deconstruction still did take place.

Table 11 Main preconditions for deconstruction

Category	Main preconditions
1. Deconstruction process	1.1 Building sequence information is archived to share with future demolition contractor
	~~1.2 Deconstruction techniques do not take additional time and are feasible~~
	1.3 Certainty on deconstruction time and recovery rate
	1.4 Objects are relatively easy to deconstruct
	1.5 Storage facility is available
	1.6 Elements with standardized dimensions
2. Deconstruction products	2.1 Material is of high quality
	2.2 Second hand materials are demanded
	2.3 Financial case is clear and profitable

The preconditions consist of partly technical preconditions, which are 1.4 (easy to deconstruct), 1.6 (standard dimensions) and 2.1 (high quality material). The other process preconditions have a focus on process. The other product preconditions focus on the financial or market aspects. Summarizing, this means preconditions in three areas are present: technical, process and financial / market.

The market preconditions are the most important, because the 'raison d'être' of every company is to make profit. Therefore, a clear and profitable financial case is necessary. This is strongly related to the demand for second hand materials. By having a demand for second hand materials, revenues are created by meeting that demand. Revenues turn into profit when higher than the costs. The technical and process preconditions together form the set that influences the costs. Every precondition that is not present, increases the costs and therefore reduces the profit. Where the market preconditions are linked to the demand, the technical and process preconditions together form the supply. Therefore, the individual technical and process preconditions have a smaller impact.

Not every precondition can be realised by an individual construction company equally easy. Three categories can be identified, respectively: direct influence, future influence and sector influence. Direct influence means the preconditions can be met in present projects by an individual construction company. Future influence means construction companies can take action now, to meet preconditions in the future. Sector influence means actions of the whole construction sector are necessary to meet the preconditions.

Direct influence:

This category contains preconditions: “1.1 Building sequence information is achieved to share with future demolition contractor” and “1.5 Storage facility is available”.

Precondition 1.1 can relatively easy be met because construction companies already create this information when designing a building. For meeting the precondition, a next step is needed, to save the information till the building is deconstructed and at that time share it with the deconstruction company. In some cases, a renovation will take place, before total deconstruction. When this happens, the information should be transferred to the renovation party. For existing buildings, information often is not available. But a part of the information can be inventoried relatively fast and inexpensive by modern techniques as 3D-scanning. This does not generate all wanted information, but does generate the floor plans of a building which contain information about dimensions.

Precondition 1.5 can be met by a construction company because it is about generating space for storage of materials. If this space is not available at the construction site, the construction company can look into other locations for storage. Logistic hubs are often used for material supply at inner-city construction projects. They can also be used for the logistics of second hand materials away from the construction site.

Future influence:

This category contains preconditions: “1.3 Certainty on deconstruction time and recovery rate”, “1.4 Objects are relatively easy to deconstruct”, “1.6 Elements with standardize dimensions” and “2.1 Material is of high quality”.

Precondition 1.3 partly depends on both technical aspects of the building and on experience of the (de)construction company. Experience will be increased automatically when applying deconstruction. But this experience only applies to similar buildings in terms of construction technique. Therefore, construction companies can stimulate this precondition by using standard building techniques. Both precondition 1.4, 1.6 and 2.1 at this moment, rely on the deconstruction techniques used in the past. No influence can be exercised on the existing buildings. However, this can be done in future building projects. Construction companies can use high quality materials with standard dimensions and make use of mechanical connections to make materials easy to deconstruct. This complies with the current trend in the construction sector of prefabrication and modularisation.

Sector influence:

This category contains preconditions: “2.2 Second hand materials are demanded” and “2.3 Financial case is clear and profitable”.

Precondition 2.2 and 2.3 are closely related to each other. For meeting precondition 2.3, at least a mild form of 2.2 is necessary. To have a profitable financial case, materials must be sold and therefore a demand is necessary. This demand can very well be created by construction companies, but not by a single construction company. The development of a proper second hand material market is needed. Such a market cannot be created by a single construction company because the created demand will not be big enough. Incentives from outside the construction sector can come from both clients and the government. Clients can demand the use of second hand materials in their projects, give more time for deconstruction projects and reserve money for deconstruction. The government can introduce legislation which raises taxes on waste (so demolishing becomes more expensive), obliges an X percentage of second hand materials in construction projects or lower tax on man hours (so the deconstruction process becomes less expensive).

Furthermore, in all case studies, it turned out the deconstruction strategies (reuse, remanufacture and recycle) are used parallel to each other. The deconstruction company makes an inventarisation of all materials in the building. As a result, every material can be deconstructed by using a different strategy and therefore a project can contain all deconstruction strategies.

By using the preconditions, a construction company can assess the possibilities for deconstruction. This makes construction companies more aware of the options for deconstruction and therefore stimulates them in the transition towards a circular economy.

Limitations

The research contains four main limitations, which are stated in the following paragraph. Each limitation creates a demand for future research, which is outlined in the next section.

The goal of this research is to analyse the most important preconditions per value retaining deconstruction strategy. However, in the case studies all three deconstruction strategies: reuse, remanufacture and recycle, were used parallel to each other. The deconstruction company determines the most suitable strategy for each individual material. So, one deconstruction project can contain all different deconstruction strategies. In the case studies it turned out parallel use of the deconstruction strategies happens all the time. Therefore, in this research the deconstruction strategies were combined as one category: deconstruction. This results in a set of preconditions that are applicable to deconstruction in general, instead of differentiated per deconstruction strategy.

The scope of the research includes buildings with at least 1.000m2 floor surface. Which automatically excludes all smaller buildings, for example dwellings. The scope also excludes the Brand layers 'services' and 'stuff'. Both services and stuff have their own value and demand at second hand markets, which might very well influence the total costs and benefits of demolition versus deconstruction. Because 'services' is a layer with relatively high value materials, it is expected to positively influence the possibility for deconstruction. This is because for high value materials the relative man hour costs are lower, because the materials are worth more. On the other hand, the impact is reduced because, in terms of volume or mass, services is only a limited part of a building.

The research contains case studies and makes use of market prices that apply at the time of research. Besides this, the assumption is done that all deconstructed materials will be sold at the second hand market and therefore no material has to be tossed away in a deconstruction situation. It is expected that between 95 and 100% of the materials will be sold in practice, the exact rate is not researched because materials can be sold a long period after deconstruction has taken place and therefore after the research.

For the sale of the materials, the influence of the market always is present. This means prices fluctuate by up- and downturns in economy, legislation, scarcity of materials and the public opinion. Up- and downturns of the economy can both increase and lower prices by an increase in demand. Legislation can lower the price by reducing tax on second hand materials or on labour costs. The scarcity of materials can make materials more expensive and therefore increase the demand for second hand materials. The public opinion can shift, wherefore sustainability becomes more important in relation to costs, which also increases the demand for second hand materials.

When looking into additional time for deconstruction, only additional man hours were taken into account. This is by far the biggest expense, but other costs also are present. A construction project is also subject to costs for security, equipment and for example the shack for breaks of the workers. Besides this, the finishing date of the project has financial implications for the building owner. Every day the building still is under construction, it cannot be exploited and therefore does not generate revenues for the client.

Future research

This research identified preconditions for the deconstruction of buildings. However, no conclusions are drawn upon how to reach those preconditions. This might be examined by executing a more in-depth case study about the identified preconditions. One can take the identified preconditions as a starting point, to look into opportunities to reach them.

This research focusses on buildings of at least 1.000m2, but it is interesting to find out if the preconditions also hold for buildings under 1.000m2. Which means expanding the scope from relatively big buildings to individual dwellings. Connecting, the influence of the layer 'services' can be incorporated, especially because it is identified as high potential for reuse. This will give a broader view of buildings as a whole, because nowadays the services are a substantial part of the building.

A snapshot of market prices and buy rates is made in this research. Which means market prices, the demand at the market and buy rates are all determined by looking at the numbers of the time of the research. To make more valid statements about these numbers, a study to the long-term behaviour of these numbers is needed. When conducting such a study, it is important to look at prices of both new and second hand materials, because the difference between them is relevant. Another aspect, besides price, might be the interest of clients in reusing materials. This is an important predictor for the price of second hand materials in the future. In general, it is interesting to do research about the preconditions for a second hand materials market.

As mentioned in the limitation section, only man hours were taken into account regarding additional costs for a longer deconstruction process. Two additional costs factors are identified: general deconstruction costs and loss of income, because the new building is finished at a later date. Especially the loss of income is interesting to study further, because this is expected to be a relative high amount of money and because it directly influences the client.

Recommendations for practice

The recommendations are mainly based on construction companies, but might also be applicable for the clients of the construction companies, for example building owners. Recommendations are made regarding process / information and financial / market aspects, because the technical aspects of existing buildings are fixed.

Process:

- For construction companies to secure information concerning buildings that are being constructed or rebuild, for example in a BIM-model. The presence of this information makes deconstruction more likely to happen. Deconstruction possibilities can be identified by making use of information about the building, for example material properties and their connections;
- For construction companies to start thinking about incorporating second hand materials already in the development stage of a project, as in this stage design freedom is still present. This can be done by inventarising a building, using the preconditions for deconstruction. This inventarisation makes clear what materials are suitable for reuse, remanufacturing or recycling and therefore can be integrated in the design of the new building;
- For construction companies to take into account physical space for storing materials when arranging construction site logistics. Reverse logistics is a more complex discipline when deconstructing, instead of demolishing. Deconstructing ensures more material streams because more materials are transported separately to various places. Physical space is needed to make sure second hand material transportation is fully loaded;
- For building owners to allow more time for deconstruction. More time means more time to deconstruct and sell materials. Usually, the deconstruction company is selected in a very late stage, when doing this earlier there is more time for selling materials and therefore more potential to deconstruct. Big clients like the housing corporations and big investment parties have the power to give more time and to enforce value retention.

Financial / market:

- For construction companies to incorporate second hand materials in new projects. These materials can be harvested at the project itself, at other projects or bought at deconstruction companies. Therefore, a demand for second hand materials is created. Using materials of own projects partly executes the risk of the market prices. Materials with standard dimensions and mechanical connections are well suited for this purpose, because they are easier to use for construction;
- For construction companies to incorporate the reuse of materials in the contracts with deconstruction companies. Deconstruction companies will need a stimulus to move from demolition towards deconstruction. This stimulus can be given in the form of a contractual obligation.

It is expected that the execution of these recommendations contributes to value retention by the use of deconstruction and therefore contributes to the transition from a linear to a circular economy.

ACKNOWLEDGEMENTS

Koopmans Bouwgroep b.v. is thanked for providing case objects and expert information about the demolish and deconstruction process of buildings. Furthermore, I would like to thank dr. J.T. Voordijk, dr. S. Bhochhibhoya and ir. N. Nielen for their inspiration, motivation and critical reviews.

REFERENCES

Adams, K. T., Thorpe, T., Osmanin, M., & Thornback, J. (2017). Circular economy in construction: current awareness, challenges and enablers. *Waste and Resource Management*, 15-24. doi:10.1680/jwarm.16.00011

Akbarnezhad, A., Ong, K., & Chandra, L. (2014). Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction*, 131-144. doi:10.1016/j.autcon.2013.10.017

Akinade, O., Oyedele, L., Ajayi, S., Bilal, M., Alaka, H., Owolabi, H., . . . Kadiri, K. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, 3-13. doi:10.1016/j.wasman.2016.08.017

Alba Concepts. (2018). *Circulaire business modellen.*

Anastasiades, K., Blom, J., Buyle, M., & Audenaert, A. (2020). Translating the circular economy to bridge construction: Lessons learnt from a critical literature review. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2019.109522

Asif, F. M., Lieder, M., & Rashid, A. (2016). Multi-method simulation based tool to evaluate economic and environmental performance of circular product systems. *Journal of cleaner production*, 1261-1281. Retrieved from https://doi.org/10.1016/j.jclepro.2016.08.122

Braakman, L. (2019). *Assessing Life Cycle Costs over increasing Building's Circularity Level.* Enschede: Universiteit Twente.

Brand, S. (1994). *How Buildings Learn: What Happens After They're Built.* Viking Press.

Brown, L. (2006). *Eco-economy update.* Earth Policy Institute.

Chini, A. (2007). General issues of construction materials recycling in USA. *Sustainable construction, materials and practices: Challenges of the industry for the new millenium.* Lisbon.

CIB CSIR. (2000). *Building Deconstruction.* Pretoria - South Africa.

Cramer, J. (2009). *10R Strategieën.*

Cruz Rios, F., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *International Conference on Sustainable Design, Engineering and Construction*, (pp. 1296-1304). doi:10.1016/j.proeng.2015.08.485

CSIR CIB B. (2000). *Overview of Deconstruction in Selected Countries.* Pretoria - South Africa.

Densley Tingley, D., Cooper, S., & Cullen, J. (2017). Understanding and overcoming the barriers to structural steel reuse, a UK perspective. *Journal of Cleaner Prodution*, 642-652. doi:10.1016/j.jclepro.2017.02.006

Ellen MacArthur Foundation. (2013). *Towards the Circular Economy: Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation. Retrieved from Circular Economy: https://www.ellenmacarthurfoundation.org/

Geldermans, R. (2016). Design for change and circularity - accomodating circular material & product flows in construction. *SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep* (pp. 301-311). Tallinn and Helsinki: Energy Procedia 96. doi:10.1016/j.egypro.2016.09.153

Gorgolewski, M., & Morettin, L. (2009). The process of designing with reused building components. *The process of designing with reused building components* (pp. 105 - 109). Rotterdam: in-house publishing. doi:978-90-9024420-4

Graedel, T., Allwood, J., Birat, J., Buchert, M., Hagelüken, C., Reck, B., . . . Sonnemann, G. (2011). What do we know about metal recycling rates? *Journal of Industrial Ecology*, 355-366. doi:dx.doi.org/10.1111/j.1530-9290.2011.00342.x.

Guillen, A., Crespo, A., Gómez, J., González-Prida, V., Kobbacy, K., & Sharrif, S. (2016).

Building Information Modeling as Assest Management Tool. *Building Information Modeling as Assest Management Tool* (pp. 191-196). Seville: International Federation of Automatic Control. doi:10.1016/j.ifacol.2016.11.033

Guy. (2011). Design for reuse of building materials in the US. *World Sustainable Building Conference*, (pp. 491 - 501). Helsinki.

Hart, J., Adams, K., Giesekam, J., Densley Tingley, D., & Pomponi, F. (2019). Barriers and drivers in a circular economy: the case of the built environment. *Procedia CIRP*, 619 - 624. doi:10.1016/j.procir.2018.12.015

HEVO. (2018). *Trends in circulaire huisvesting.* Den Bosch: HEVO.

Hsu, P.-Y., Aurisicchio, M., & Angeloudis, P. (2019). Risk-averse supply chain for modular construction projects. *Automation in Construction*. doi:10.1016/j.autcon.2019.102898

Iacovidou, E., & Purnell, P. (2016). Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. *Science of the total environment*, 791-807. doi:10.1016/j.scitotenv.2016.03.098

Jauregui, R. (2017). *ADOPTION OF MODULAR INNOVATIONS IN THE DUTCH.* Enschede: University of Twente.

Jensen, J. P., Prendeville, S. M., Bocken, N. M., & Peck, D. (2019). Creating sustainable value through remanufacturing: Three industry cases. *Journal of Cleaner Production*, 304-314. doi:doi.org/10.1016/j.jclepro.2019.01.301

Kibert, C. (2016). Sustainable construction: green building design and delivery. John Wiley & Sons.

Kircherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation & Recycling*, 221-232. doi:10.1016/j.resconrec.2017.09.005

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: The concept and its Limitations. *Ecological Economics*, pp. 37-46. doi:10.1016/j.ecolecon.2017.06.041

Lansink, A. (1980). *Ladder van Lansink*. Retrieved from Ad Lansink: http://www.adlansink.nl/voorbeeld-pagina/

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, 976-989. doi:10.1016/j.jclepro.2017.12.010

Mahpour, A. (2018). Prioritizing barriers to adopt circular economy in construction and demolition waste management. *Resources, Conservation & Recycling*, 216-227. doi:10.1016/j.resconrec.2018.01.026

Mangla, S. K., Luthra, S., Mishra, N., Singh, A., Rana, N. P., Dora, M., & Dwivedi, Y. (2018). Barriers to effective circular supply chain management in a developing country context. *The Management of Operations*, 551-569.

Michelini, G., Moraes, R. N., Cunha, R. N., Costa, J. M., & Ometto, A. R. (2017). From linear to circular economy: PSS conducting the transition. *Procedia CIRP*, 2-6. doi:10.1016/j.procir.2017.03.012

Mignacca, B., Locatelli, G., & Velenturf, A. (2020). Modularisation as enabler of circular economy in energy infrastructure. *Energy Policy*. doi:10.1016/j.enpol.2020.111371

Mihelcic, J. R. (2003). Sustainability Science and Engineering: The Emergence of a New Metadiscipline. *Environmental Science & Technology*, 5314-5324. doi:10.1021/es034605h

Milios, L., Beqiri, B., Whalen, K. A., & Jelonek, S. H. (2019). Sailing towards a circular economy: Conditions for increased reuse and remanufacturing in the Scandinavian maritime sector. *Journal of Cleaner Production*, 227-235.

Nasir, M. H., Genovese, A., Acquaye, A. A., Koh, S., & Yamaoh, F. (2017). Comparing the linear and circular supply chains: A case study from the construction industry. *Int. J. Production Economics*, 443-457. doi:10.1016/j.jipe.2016.06.008

Parto, S., Loorbach, D., Lansink, A., & Kemp, R. (2007). Transitions and institutional change: The case of the Dutch waste system. *Industrial innovation and environmental regulation: developing workable solutions*, 233-257.

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production*, 710-718. doi:10.1016/j./jclepro.2016.12.055

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: measuring innovation in the product chain.* Utrecht: PBL Netherlands Environmental Assessment Agency.

Rashid, A., Asif, F. M., Krajnik, P., & Nicolescu, C. M. (2013). Resource Conservative Manufacturing: an essential change in business and technology paradigm for sustainable manufacturing. *Journal of Cleaner Production*, 166-177. Retrieved from https://doi.org/10.1016/j.jclepro.2013.06.012

Reike, D., Vermeulen, W. J., & Witjes, S. (2018). The circular economy: New or Refurbished as CE 3.0? — Exploring. *Resources, Conservation & Recycling*, 246-264. doi:10.1016/j.resconrec.2017.08.027

Rijkswaterstaat. (2013). *Nederlands afval in cijfers, gegevens 2006-2010.* Rijkswaterstaat.

Sanchez, B., Rausch, C., & Haas, C. (2019). Deconstruction programming for adaptive reuse of buildings. *Automation in Construction*. doi:10.1016/j.autcon.2019.102921

Shirowzhan, S., Sepasgozar, S., Edwards, D., Li, H., & Chen, W. (2020). BIM compatibility and its differentiation with interoperability challenges as an innovation factor. *Automation in Construction*. doi:10.1016/j.autcon.2020.103086

Silva, R., De Brito, J., & Dhir, R. (2017). Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. *Journal of Cleaner Production*, 598-614. doi:10.1016/j.jclepro.2016.12.070

Sitcharangsie, S., Ijomah, W., & Wong, T. (2019). Decision makings in key remanufacturing activities to optimise remanufacturing outcomes: a review. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2019.05.204

TNO. (2013). *Opportunities for a circular economy in the Netherlands.* Delft: TNO.

TNO. (2015). *Amsterdam Circulair.* Amsterdam: Gemeente Amsterdam.

Urbinati, A., Chiaroni, D., & Chiesa, V. (2017). Towards a new taxonomy of circular economy business models. *Journal of Cleaner Production*, pp. 487-498. doi:10.1016/j.jclepro.2017.09.047

Van den Berg, M., Voordijk, H., & Adriaanse, A. (2019a). Recovering building objects for reuse (or not).

Van den Berg, M., Voordijk, H., & Adriaanse, A. (2019b). Information processing for end-of-life coordination: A multiple-case study.

Van Odijk, S., & Van Bovene, F. (2014). *Circular Construction. The foundation of a renewed sector.* ABN AMRO.

Volk, R., Stengel, J., & Schultmann, F. (2014). Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction*, 109-127. doi:10.1016/j.autcon.2013.10.023

Voordijk, H., de Haan, J., & Joosten, G.-J. (2000). Changing governance of supply chains in the building industry: a multiple case study. *European Journal of Purchasing & Supply Management*, 217-225.

Wilson, V. (2011). Research Methods: Content Analysis. *Evidence Based Library and Information Practice,* 177-179. doi:10.18438/B86P6S.

Wohlin, C. (2014). *Guidelines for Snowballing in Systematic Literature.* Karlskrona: Blekinge Institue of Technology. doi:10.1145/2601248.2601268

World Economic Forum. (2014). *Towards the Circular Economy: Accelerating the scale-up across global supply chains.* Genève: World Economic Forum.

Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2019.118861

Yan, J., & Feng, C. (2014). Sustainable design-oriented product modularity combined with 6R concept: a case study of rotor laboratory bench. *Clean Technologies and Environmental Policy*, 95-109. doi:dx.doi.org/10.1007/s10098-013-0597-3.

Yin, R. (1994). *Case study research, Design and methods.* Sage Publications: Thousand Oaks.

Zahir, S. (2015). *Approaches and Associated Costs of Building.* Michigan: Michigan State University.

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, 593-602. doi:10.1111/jiec.12545

APPENDIX I INTERVIEW FORMAT

Category	Main preconditions	Questions
Deconstruction process	Building sequence information is archived to share with future demolition contractor	Is the construction method of the building clear and available to deconstruction company?
	Deconstruction techniques do not take additional time and are feasible	Is deconstruction more time consuming than demolishing? If yes, why is this / where is the main difference?
		Does the demolishing company identify possibilities for deconstruction?
		Is the demolishing company able to deconstruct the building without additional costs?
		Is the demolishing company able to guarantee the quality of the material till placement in a new building?
	Certainty on deconstruction time and recovery rate	Is the timespan of deconstruction clear?
		Is the recovery rate known?
	Objects are relatively easy to deconstruct	Are the connections between objects reversible?
		Are mechanical connections used?
		Are the connections reachable?
		Is the number of connections relatively small? (in comparism to other buildings)
	Storage facility is available	Is there a possibility to store materials?
	Elements with standardized dimensions	Do the objects have standard dimensions?
Deconstruction products	Material is of high quality	Is toxic material present?
		Can the material serve as an input for a new building?
	Second hand materials are demanded	Is there a market for the 2nd hand material?
		Is the demand clear?
		Is there a demand for the 2nd hand material?
	Financial case is clear and profitable	Is the cash flow of deconstruction clear?
		Is there an financial advantage for deconstruction in relation to demolishing?
		Is the market value of the recovered materials clear?
		Are the recovered materials of high value?
		Are the disposal costs of the material high? (which part of the total cost)
		Are the deconstruction costs relatively low?

APPENDIX II CASE DESCRIPTION

#1 – Hesselink Koffie

Hesselink Koffie is an ambitious company that devotes great care to sustainable solutions. For this reason, the client strives for a BREEAM In-Use certification for the new hall. So, the client is intrinsically motivated to retain value of the existing building and contractually recorded this by making sure two window frames of the to be deconstructed façade would be reused. All other value retaining actions were initiated during the construction phase. The two existing halls are constructed out of a steel frame with sandwich façade elements and a concrete floor. They consist of a combined office and production hall in the one hall and a storage facility in the second. Both halls are about 30 years old. The task is to build a hall between the to, to connect them. The function of this new hall will be to house

the distribution and make it possible to load the trucks at a roofed place.

Object properties

Site:

The existing foundation totally consists of concrete and will stay it its place. This is because the project mainly contains an expansion.

Structure:

The structure of the building consists of a ground floor that consists of reinforced concrete and is placed on sand. Steel columns are placed to attach the façade to and to carry the roof. The roof is made out of sandwich panels, which consist of two layers of steel with insulation in-between. The panels are attached by using bolts.

Skin:

The façade of the building exists of sandwich panels, masonry, aluminium curtain wall and window frames. But the part that is deconstructed contains only sandwich panels with window frames in them. These panels are fixated by bolts, so can easily be removed.

Space plan:

The hall does not contain much interior. The interior that is present, for the offices, just remains in place.

Economical preconditions: Second hand materials are demanded, but only at the project itself. Upfront the client already determined to reuse window frames, further value retention was all initiated during the project. So only the reuse of the two window frames was determined in the contract. (1.31) Façade sandwich panels, OSB panels and more window frames are materials that are reused at this project, so they are demanded. The client himself is very active in searching for second hand materials, he for example arranged a second hand stairs and glass inner walls. Because the client is very interested in sustainability, be he is intrinsically motivated to reuse materials. He is even willing to pay a little more when this means a certain material can be reused. The client also created the demand for a second hand crash barriers, which is needed in the new hall. The construction company looked at the market for such a barrier and found out the barrier is deliverable but will cost more than a new one. Before the start of the project the financial case was not clear, because many decisions were made during construction phase. The project was started with a traditional contract with a fixed price and no obligations about reuse except for the two window frames. The prices for new materials and prices for the disposal of waste are known at the construction company. The prices for new materials can easily be retrieved from suppliers, or by past experience. The costs for waste disposal are standard because of framework agreements. Next to the standard price, the price also is very low. For example, the price of a container full of demolishing waste costs 350 euros. It is estimated that at this project about 5 to 7 containers are needed. In relation to the project budget this is only 0,1%. The costs for second hand materials and for deconstructing materials is hard to estimate for the construction company. It is known that deconstruction does take more time than demolishing, but how much is unknown. For the construction company the materials that are deconstructed and spare the purchase of a new material, save the amount of money a new material would have costed.

* kept in place Manhour €40,-			Case 1 - Hesselink						
		Unit	Deconstruction costs	Demolishing costs	Salvage value	Waste costs	Total Deconstruction	Total Demolishing	Difference
Total			**€ 5.377**	**€ 849**	**€ 6.544**	**€ 4.964**	**€ -1.167**	**€ 5.813**	**€ -6.981**
Site			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Foundation*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Structure			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Concrete structure*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Steel column	4	#	€ 152	€ 24	€ 690	€ -136	€ -538	€ -112	€ -426
Skin			**€ 4.180**	**€ 660**	**€ 5.984**	**€ 4.964**	**€ -1.804**	**€ 5.624**	**€ -7.429**
Insulated steel sandwich panels*	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Window frame	8	#	€ 1.216	€ 192	€ 1.044	€ -192	€ 172	€ -0	€ 172
Insulated steel sandwich panels	260	m2	€ 2.964	€ 468	€ 4.940	€ 5.157	€ -1.976	€ 5.625	€ -7.601
Space plan			**€ 1.197**	**€ 189**	**€ 560**	**€ -**	**€ 637**	**€ 189**	**€ 448**
OSB panels	105	m2	€ 1.197	€ 189	€ 560	€ -	€ 637	€ 189	€ 448

Deconstruction process preconditions:

Deconstruction does take more time than demolishing. This is because deconstructing is manual work and demolishing can be done by an excavator. One has to be carefully when deconstruction, because the materials cannot be damaged afterwards. Especially with sensitive materials as façade sandwich panels, a sink or glass walls this is extra important. On the other hand, it does not have to be a problem that deconstruction takes more time. Because the consideration for value retention is made between an increase in costs by additional time when deconstructing and a decline in costs because of lower purchasing costs. At this project the façade panels at the front of the hall were kept in place, where after a wooden frame is placed in front of it to close the façade and give it the wanted look. This method was estimated to be cheaper by the construction company because less time would be needed because of not demolishing the façade. Another reason is that less material has to be purchased, because the existing façade already had enough insulation in it. The costs exist of applying the wooden frame in front of the façade. It turned out the façade was not completely straight, so the wooden frame took way more time to product than estimated. A storage facility is extremely important when materials should be reused. This project has a big, spacious construction site, so enough storage space. (1.20 – 1.22). Next to the construction site there is also is place in the existing halls, to store materials. The need for storage has two reasons. At first, when you want to sell materials you have to bring supply and demand together, which might take some time. In this time the materials have to be stored. The second option is the reuse at the same project, which is done in this case. At the start of a project some parts are deconstructed, which can be reused later on. But because there is time between deconstruction and construction the materials should be stored. For example, the sandwich facade panels, they had to be deconstructed to place the steel structure for the new hall. On this steel structure the sandwich facade panels are placed back.

Object properties preconditions: The ability to deconstruct a material depends mainly on the connection. In general chemical connections cannot be loosened, while mechanical connections can. However, not all mechanical connections can be loosened. When a screw is rusted or placed in hard wood it often will snap. For the example of window frames there are quite some connections, that are not accessible. Because they often are placed in a masonry wall. The bolts of sandwich panels are accessible and because they are placed concealed, they are in good condition. At this project the window frames were deconstructed, this was possible because they were not placed in a masonry wall, but in the façade that consists of plates. The window frames still were of good quality and could be reused without adaption in the new wall. Asbestos was situated under the window frames, but not attached to it. So, this could easily be removed after deconstructing the window frames. Of all objects that were reused in this project only the façade sandwich panels have standardized dimensions. Because of these standard dimensions they could easily be reused to fill up an opening in the façade. Another reason for reusing these panels is that new panels often have a different standard dimension and these have been at the building already so they are coloured because of the weather. The osb plates also have standard dimensions, a multiple of 61, but when they will be reused some of them have to be adapted to the new dimensions of the wall, they will be processed in.

Value retaining deconstruction strategies: A lot of value retaining DS are applied at this project. They are listed below:

- Sandwich panels out of the façade are reused in the façade (at construction company initiative). They could remain in place and would be the basis for the new façade.
- Other sandwich panels of the façade had to be removed to create an opening. Those are reused to close an opening at the back of the building. This is outsourced to the façade subcontractor. The reason is both environmental and because it is hard to buy the same profile and color of façade panel for a hall like this.
- Temporary wall of osb board will be remanufactured to create an inner wall instead of using gypsum plates. This is not reuse but remanufacturing because of the change in dimensions. This particular form of reuse will be cheaper for the client, mainly because the material is as good as new.
- Crash protection might be used of old highway crash barriers. This is more expensive, purely because the highway barriers are more expensive to buy.

The used concrete for the floor and foundation contains 30% used concrete as aggregate.

#2 – Cruquius Sigma

Cruquius Sigma is part of the bigger part Cruquius, which is located at Cruquiuseiland in Amsterdam. The whole island is transformed from an industrial area to a residential area. The client is a big pension fund that is specialized in area development. Cruquius Sigma consists of building A & B of the total 6 buildings in the Cruquius project. Building A is a monument and building B a production facility out of 1920. There are no specific demands regarding value retention by both the client or the municipality of Amsterdam. The municipality does have one demand regarding the window frames of the monument, they should be the exact same profile and look as the current situation is.

* kept in place Manhour €40,-			Case 2 - Cruquius						
		Unit	Deconstruction costs	Demolishing costs	Salvage value	Waste costs	Total Deconstruction	Total Demolishing	Difference
Total			**€ 411.667**	**€ 65.000**	**€ 18.798**	**€ -3.463**	**€ -18.798**	**€ -3.463**	**€ -15.335**
Site			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Piles*	0	#	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Foundation*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Structure			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Concrete structure*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Concrete	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Sand limestone	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Steel column	0	#	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Skin			**€ -**	**€ -**	**€ 18.798**	**€ -3.463**	**€ -18.798**	**€ -3.463**	**€ -15.335**
Masonry	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Masonry	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Metal window frame	144	#	€ -	€ -	€ 18.798	€ -3.463	€ -18.798	€ -3.463	€ -15.335
Space plan			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Steel stairs	0	#	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Ceramic tiles	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -

Object properties

Site:

Constructed on wooden piles (***2.22 Cruquius Blok B tekening).*** On top of the wooden piles reinforced concrete was used to complete the foundation.

Structure:

The structure consists of columns made of reinforced concrete. These columns are the connection between two floors, which also are made of reinforced concrete. (***2. Cruquius Sigma foto***)

Skin:

The skin exists of masonry with steel window frames in it. The masonry starts at the foundation and ends at the top of the building. Because of the connection of the stones by cement this has become one big object. The window frames are placed in the masonry, they are fixated by screws.

Space plan:

The space plan consists of masonry walls with steel and wood door frames in it. The door frames and doors have a height of 210cm, which is too low for the current legislation. In this building there are no additional floors or lowered ceilings.

Economical preconditions: At this project there was a financial benefit to keep the concrete structure standing. This saves money because the construction company does not have to buy new materials. Another benefit is that it shortens the total project time, in this case even with a couple of months. A disadvantage is the dimension of the existing structure, all bay dimensions are slightly different.

So, everything that is attached to the structure should be custom made and there is no standard in those dimensions. This takes more time because of measuring and also brings the risk of objects not exactly fitting in the current concrete structure. Then there is an additional risk because of retaining the concrete structure, because it is on wooden piles which have to be kept wet by the groundwater. Because of constructing another building next to this project, a building pit surrounded by dam walls is installed. Normally the company would use drainage to keep the building pit dry, but at this project retour drainage was also needed to keep the foundation piles wet. A demand for the window frames is identified, because they will need to return in the same project. For the reuse of the window frames there is the disadvantage that the facade is completely open and the window frames are gone for restauration during 3 to 5 months. This brings the additional cost of building a temporary facade closure. There is no difference between the price for renovation of the existing window frames or the price for buying new window frames. The difference in time and thereforee costs is in the additional time for deconstruction the window frames and then the time when the façade is open, so should be filled with a temporary window frame.

Deconstruction process preconditions: Most of the building in this project was demolished, expect for the concrete structure and the façade of the monumental building. This saves deconstruction time because the existing concrete structure is kept in place. This saves both demolishing and construction time. Which has the effect that everything that will be placed at the structure needs more time, because everything has to be custom made. On the other hand, deconstructing the window frames takes way more time. Because they will be renovated every screw has to be unscrewed by hand, which is a time-consuming process. The glass in the window frames is fixed with asbestos putty, which needs a special deconstruction technique because asbestos is a toxic material. For the window frames, this is the only difference in timespan. The renovation or production of a new window and afterwards the placement does not take more or less time than placing a new window frame. No other objects were deconstructed because they were considered of too low value by the deconstruction company. The main reason is that the building is 100 years old and had contained a factory.
Object properties preconditions: The concrete structure and foundation beneath it have such a high quality that they can remain in place and be reused for the new building. The building was already designed for adding two additional floors, which will also happen. The window frames are the only objects that are remanufactured. Deconstructing them is not easy because of the asbestos putty the glass is fixated with. All other objects in the building are so old they don’t have value anymore.

Value retaining deconstruction strategies: The concrete structure and foundation beneath it are reused in this case. The window frames are remanufactured, they are being renovated by a specialized company and placed back in the same function afterwards. The final value retention is a very specific one. Two old scales, which were in the factory, are stored by the construction company. They are stored for two future residents of the to be built houses.

#3 – Ricardo Residences

Ricardo Residences is a transformation project of a 40.000m^2 office building to 365 apartments. The client is the real estate department of a big pension fund. This project is unique because the building is only fifteen years old and it is already being transformed from offices to houses. Another unique aspect of the project is that great amount of time the deconstruction company has. They already started in August, while the construction company just started in February. So for 7 months they were alone at the project and had all the time and space to deconstruct and sell objects.

The deconstruction costs for the construction company are 1.4 million euros. This includes stripping the whole building till the concrete structure and demolishing the two top floors. These

have to be demolished because they differ in appearance. They will be newly built afterwards.

Object properties

Site:

The building is constructed on a concrete foundation that is built on bored concrete piles. The foundation and the piles are connected to each other by pouring concrete filled with iron rebar. The coupling between foundation and structure is done by applying iron pins in both parts and securing them with concrete. This connection is used at both the prefab and the in-situ concrete. While this is a chemical, non-reversible connection, the materials in the site are very hard to deconstruct.

Structure: ***3.23 Ricardo Details***

The structure exists of prefab walls, prefab columns and prefab floors, which are both wide slab floors and hollow core floors. The floors always lay on a thickening in the wall. There are two different options, or they lay without connection, or they are fixated with an iron pin and concrete. For the hollow core floors only the joints between two plates are filled with concrete, while the wide slab floors are topped up with concrete in total so they become one big concrete plate. Additionally, a concrete layer is sometimes added on top of the hollow core floors, for constructive safety. So, the only reuse potential is for the hollow core floors, when the in-situ poured concrete can be separated from the prefabricated part. In theory this is possible, but practice shows this is a very long process. Another risk for doing this is damaging the prefab part and thereforee lowering the quality of the element.

Skin: ***3.23 Ricardo Details***

The concrete columns in the structure hold the aluminum curtain wall, which is part of the skin, using consoles. The consoles are applied by bolts which thereforee is a reversible connection. Other parts of the façade consist of masonry which is connected with galvanized wall ties to the concrete structure. Masonry exist of stones connected by cement, in which the ties are placed also, so a non-reversible connection. So the aluminum curtain wall is potentially suited for deconstruction, because of the reversible connections it can be deconstructed without damaging the elements. The masonry wall is not suitable for deconstruction because it consists of brick with cement joints, which is a chemical connection.

Space plan:

The space plan contains floor tiles that are not glued to the floor, so can easily be deconstructed. The floor tiles are applied before inner walls are placed, so no cutting waste is present for the intersections with the walls. The biggest part of the floor tiles still are nice and clean. They have standard dimensions, every tile has the same dimensions. There is some loss because the inner walls are placed on top of them. To attach those inner walls u-profiles are applied on top of the floor tiles. They are attached using bolts, which go through the floor tiles into the concrete floor below. The inner walls on this project are both filled walls and glass walls. (***Picture Dynatos 48***). The walls are built between two u-profiles that are on the floor and at the ceiling. At the floor where the picture was taken, the floor height is higher than on other floors. Normally the upper and lower panel of a wall, which is on the picture, exactly match the height o f a floor. The wall panels also have the same width and thereforee have standard dimensions. The glass walls do not change in color, but the filled walls do after some time. Newer buildings are built with other colors of walls and the walls that are in used buildings change color because of aging. The window frames and door that are applied in the inner walls also have standardized dimensions. They have the standard floor height and at the floor that is higher, glass panels are used to increase the height. This standard dimension increases the potential for reusing them in another building, because no adaptions in design have to be made. It already consists of the standard height for office buildings. The inner walls and window frames are connected to each other with bolts, which can easily be removed. The ceilings are the last object out of the space plan. They are attached to the floor above by iron bars that are chemically connected. However, the ceilings can be deconstructed from the iron bars. The ceiling consist of an aluminum frame with ceiling plates laying on top, without fixation. So the plates are easy to deconstruct. ***Picture Dynatos 48*** shows that a lot of installations are applied through the ceiling. Installations are out of scope for this research, but they do influence the ceiling plates. Because of the often standard dimensions of installations the ceiling plates with holes in them can be reused for the same installations. But it limits the totally free reuse of the ceiling plates.

2nd hand markets:

- There is a market for a lot of material out of this project. For example 80% of the floor tiles were reused. Mostly at other projects in the Netherlands, but even abroad.
- The whole inner side of the building is deconstructed and sold to other projects. Think about inner walls, floor tiles and ceilings. The numbers are in the excel file with all the quantities in it. (Also toilets, lighting fixtures and air treatment installation (but these are out of scope).
- The materials could not be reused at the same project because of the transformation from offices to houses. Offices have a space plan that is designed for optimal working conditions. A basic characteristic of offices is that whole floors or even buildings have the same style and look of materials. This is different when looking into houses, every resident has his own expectations regarding the space plan of the building, which makes a more heterogenous space plan. For example with other types of inner doors or other colors at the wall. The second reason is the fixed image people in the Netherlands have of an office and a house. In an office building the system ceilings are accepted, but in a house people will never accept it. The glass inner walls cannot be reused in houses for the practical reason that they are transparent. Where an office nowadays should be as open and transparent as possible, houses still need separate rooms. One can image having a solid wall between living and sleeping room is a requirement of house inhabitants.
- The deconstruction company has fixed parties to sell the materials to. These parties come get the materials at the building site, so the deconstruction company only does the deconstruction and sometimes some transport at the building site. For example the inner walls are bought by a company that is specialized in 2nd hand inner walls, both filled and of glass. Because of the fixed parties to sell to the deconstruction company has a relatively stable market, at least for the materials that can easily be traded. For example floor tiles or system walls.

- Next to the demand also the supply is hard to estimate. At first it is hard to estimate when exactly the deconstruction can start. Then there can be the situation that the building has been empty for quite some time, so leakages occur and other damages arise. At this project there was a leakage at the 2nd floor, so about 1.000 m2 of floor tiles could not be reused anymore.

- For all materials mentioned at the first question there is a demand. For example, the inner walls of this project went to Groningen and Friesland. The glass inner walls sell better than the filled walls. This is because of trends, people want a certain color. If the color of these walls is different, they do not want them.

- The deconstruction contractor was working on sawing the floors of a tower and using them in another project as walls. This did not work out because at this moment the other project is already finished and soon they will start deconstructing the tower. So when the demand is clear, the next step is to create the supply (within a certain timeframe).

Financial case:

- For the deconstruction the financial routing is very clear. Additional money is invested in deconstructing, because this takes more time than demolishing. Then the materials are directly from the building site sold to a fixed party, so money is earned.

- Paper Cruz Rios Chong Grau 2015: (Deconstruction + Disposal + Processing) – (Contract price + Salvage Value) = Net deconstruction costs. Addition out of the case study, transport and storage do also cost money.

- "In the end there is no difference between deconstructing and demolishing. It took way more hours to deconstruct the building and on the other the selling of the objects delivered money. Another benefit is that less material has to be removed as waste, which also costs money. For example the floor tiles, normally they are removed by a machine that does 10m2 in 10 minutes. Now they are removed by hand, taking an hour to deconstruct 10m2 of tiles. Normally the deconstruction contractor would toss them out of the window in the container, but now he has to place them on pallets and move them vertically with the elevator.

- The disposal of waste costs money, however not much in relation to the additional hours it costs to sell the materials. Then there even are materials that bring money when disposing them, for example iron and other metals.

- Still the exact amounts of money are hard to determine because the time spent will always be an estimation. During the project there is a constant monitoring on the worked hours, when this becomes too much the deconstruction company will switch to demolishing.

- When looking a step higher, at the cash flow of the total company. The owner of the building wants to finish as soon as possible, so he can earn rent for his houses. One month of rent for a building as this would be around €400.000. This stands in no way in relation to the benefit of deconstructing over demolishing, why is already about 0.

- Because of the space in the parking garage the costs for transport could be kept as low as possible. At some moments there were more than 150 pallets of carpet tiles in the garage. At the moment the deconstruction company had a truckload a transport was ordered, so only full trucks where driving.

Deconstruction process:

3.40 Ricardo vrijkomende hoeveelheden shows the quantities that come out of the building.
It are hundreds m2 of masonry, sand-limestone, floor tiles, aluminum curtain walls and ceiling plates. Of which only the floor tiles, aluminum curtain walls and ceiling plates are sold as the same object. The masonry and sand-limestone are sold as debris.

- The original assignment of the construction company to the deconstruction company did not take any deconstruction into account. So the focus of the construction company is on the traditional way, demolition. It was the deconstruction company who proposed deconstruction and also executed it.
- The whole inner part of the building (space plan) is deconstructed. This was done using other and more work intensive methods than regularly. Normally everything would be demolished, mostly by making us of machines***. (Picture Dynatos 42)***
- All materials are sold to different retailers. So when the products left the construction site, they were no longer responsibility of the deconstruction company.
- The deconstruction times of the objects are not known. This is both because the company does not have much experience with deconstruction and because every project is an unique situation. The duration was tested by trying to deconstruct an object and measuring the time. At the same moment was tested if an object would break or not. With other words, what the recovery rate of the materials is.
- In the end there is no difference between demolishing all materials or deconstructing them. The deconstruction company made a price based on demolishing the building (except for parts that had to stay in place). But during the deconstruction phase he found out that deconstruction also was a possibility at this project. The construction company was not additionally billed for this, neither did they get money back.
- Usually there is no room to store anything at the construction site, so it is important to sell and move materials as fast as possible. At this project the deconstruction contractor had a very long time (half a year) to deconstruct the building and thereforee to store materials at the parking garage under the buildilng, but this was an unique situation. When external, a storage always costs money. This deconstruction company always sells to parties who retreive the objects at the building site, so those parties have their own storage.

* kept in place Manhour €40,-			Case 3 - Ricardo						
		Unit	Deconstruction costs	Demolishing costs	Salvage value	Waste costs	Total Deconstruction	Total Demolishing	Difference
Total			**€ 1.664.000**	**€ 262.737**	**€ 889.631**	**€ 452.296**	**€ 774.369**	**€ 715.032**	**€ 59.336**
Site			**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**	**€ -**
Piles*	0	#	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Foundation*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Structure			**€ 349.440**	**€ 55.175**	**€ 9.488**	**€ -1.870**	**€ 339.953**	**€ 53.305**	**€ 286.648**
Concrete structure*	0	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Concrete	690	m3	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Sand limestone	2483	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Steel column	55	#	€ -	€ -	€ 9.488	€ -1.870	€ -9.488	€ -1.870	€ -7.618
Skin			**€ 399.360**	**€ 63.057**	**€ 101.035**	**€ 14.674**	**€ 298.325**	**€ 77.731**	**€ 220.594**
Masonry*	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Masonry	1440	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Aluminum curtain wall*	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Aluminum curtain wall	3000	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Metal window frame	286	#	€ -	€ -	€ 37.335	€ -6.878	€ -37.335	€ -6.878	€ -30.457
Insulated steel sandwich panels	600	m2	€ -	€ -	€ 11.400	€ 11.900	€ -11.400	€ 11.900	€ -23.300
Cement-bonded fibreboard	2250	m2	€ -	€ -	€ 27.893	€ 9.653	€ -27.893	€ 9.653	€ -37.545
Insulation	4575	m2	€ -	€ -	€ 24.407	€ -	€ -24.407	€ -	€ -24.407
Space plan			**€ 915.200**	**€ 144.505**	**€ 779.109**	**€ 439.491**	**€ 136.091**	**€ 583.997**	**€ -447.906**
Floor tiles	22680	m2	€ -	€ -	€ 97.978	€ 54.054	€ -97.978	€ 54.054	€ -152.032
System ceiling	23375	m2	€ -	€ -	€ -	€ 25.323	€ -	€ 25.323	€ -25.323
System walls glass / filled	20771	m2	€ -	€ -	€ 679.587	€ 360.038	€ -679.587	€ 360.038	€ -1.039.624
System walls filled	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Ceiling plates as wall filling	0	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Steel stairs	2	#	€ -	€ -	€ 1.405	€ -400	€ -1.405	€ -400	€ -1.005
Ceramic tiles	1210	m2	€ -	€ -	€ -	€ -	€ -	€ -	€ -
Acoustic panels	20	#	€ -	€ -	€ 140	€ 477	€ -140	€ 477	€ -617

Objects / Companies		Price in €	# of objects	Price in €	# of objects	Price in €	# of objects	Price in €	# of objects	Price in €	# of objects	
		Omgekeerd bouwen		Gebruiktebouwmaterialen.com		Bloem Gebruikte bouwmaterialen		Buurman + Marktplaats		Average	Average	Average price for case
Inner door filled panel	piece	€ 40,00	12	€ 72,00	50			22,5	30	€ 44,83	23	
Inner door glass	#	€ 50,00	3	€ 155,00	4					€ 102,50	2	
Glass inner wall 2300 x 3500mm	m2	€ 35,00	8							€ 35,00	2	€ 32,72
Filled inner wall 2300 x 3500mm	#					€ 330,00	3	160	15	€ 245,00	5	€ 32,72
Tile lath 22 x 50mm	m1	€ 0,60	1400					0,75	52	€ 0,68	363	
Tile lath 50 x 50mm	m1			€ 1,50	250					€ 1,50	63	
Wood 60 x 170 x 4000mm	#			€ 19,00	22	€ 16,00	60			€ 17,50	21	
Wood 70 x 30 x 380mm	m1	€ 1,20	40							€ 1,20	10	
Wood 145 x 35 x 440mm	m1	€ 1,60	30							€ 1,60	8	
Wood cement plates 1100 x 1100 x 18mm	#	€ 15,00	35							€ 15,00	9	€ 12,40
Plywood 18mm thick	m2	€ 9,00	100	€ 9,90	655			5,00	100	€ 7,97	214	
OSB panel 1220 x 2440 x 18mm	#			€ 22,50	83					€ 22,50	21	
Water resistant OSB panel 12mm thick	m2			€ 5,71	84			5,00	6	€ 5,36	23	
HEA 180	m1			€ 35,00	26					€ 35,00		€ 172,50
HEA 280	m1			€ 80,00	12					€ 80,00		€ 172,50
Trespa with insulation 3cm thick	m2	€ 12,00	51							€ 12,00	13	
Trespa with insulation 5cm thick	m2	€ 19,00	173							€ 19,00	43	€ 19,00
Trespa 6mm thick	m2			€ 20,00	160					€ 20,00		
Sound insulation panel	#	€ 7,00	20							€ 7,00	5	€ 7,00
Insulation plate 1500 x 505 x 210mm	#	€ 9,00	44							€ 9,00	11	€ 5,33
Insulation plate 40-50mm thick	m2	€ 3,25	40					4	50	€ 3,63	23	€ 5,33
Insulation plate 1000 x 1000 x55mm	#	€ 2,50	300							€ 2,50	75	€ 5,33
Insulation plate 1200 x 1000 x 70-200mm	m2			€ 4,00	325					€ 4,00	81	€ 5,33
Plastic door	#			€ 532,00	3					€ 532,00	1	
Wood door	#			€ 186,00	150	€ 75,00	1			€ 130,50	38	
Aluminum window frame 2 windows	#	€ 350,00	3	€ 307,00	5					€ 328,50	2	€ 130,54
Aluminum window frame 1 window	#	€ 115,00	6	€ 137,50	2					€ 63,13	2	
Plastic window frame 1 window	#			€ 133,00	14					€ 133,00	4	
Plastic window frame 2 windows	#			€ 245,00	13	€ 60,00	1			€ 152,50	4	
Wood window frame 1 window	#			€ 210,00	1					€ 210,00	0	
Wood window frame 2 windows	#			€ 300,00	1					€ 300,00	0	
Steel stairs	#	€ 505,00	2	€ 900,00	1					€ 702,50	1	€ 702,50
Carpet tiles	m2							€ 4,32	224,5	€ 4,32	56	€ 4,32
PVC Floor tiles	m2	€ 9,00	16							€ 9,00	4	
System ceiling	m2							€ -	130	€ -	33	
										€ -		
		Beelen		Boverhoff		Herms		Renewi				
Construction waste		€ 255,00	9 m3			€ 235,00	9 m3	€ 225,00	9 m3	€ 238,33	26	€ 238,33
Wood		€ 123,00	6 m3			€ 112,50	6 m3	€ 127,50	6 m3	€ 121,00		
Iron		€ -200,00	1000 KG	€ -200,00	1000 KG					€ -200,00		
Aluminum		€ -650,00	1000 KG	€ -650,00	1000 KG					€ -650,00		€ 0,65
Plastic								€ 200,00	10 m3	€ 200,00		€ 0,20
Gypsium								€ 212,50	2500 KG	€ 212,50		
Concrete + Masonry (Debris)		€ -	m3	€ -	m3			€ -	m3	€ -		€ -