Disassembling the steps towards Building Circularity

Redeveloping the Building Disassembly assessment method in the Building Circularity Indicator

Colophon

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Preface

Ever since I enrolled into my bachelor Building Engineering at the Hogeschool van Arnhem en Nijmegen (HAN), my interest in the built environment, engineering and especially in new developments and innovation is triggered.

Some say that the building sector might be the wrong place to be for this, due to the relatively long time it takes for new developments to land. But when I see all the innovative concepts and ideas that are being developed, my enthusiasm increases and I argue that this is exactly the right place to be. There are so many opportunities for change in such a complex process that is building development.

Sustainable development has always been a relevant topic in scientific research and the circular economy may be the next big thing, but getting things right according to the Circular Economy principles seems to create difficulties in the built environment. This is why I wanted to contribute to this topic.

This thesis marks the end of my Construction Management & Engineering master program. The research expands on both the topics Circular Economy and Disassembly of buildings. One of them being a relatively new principle and the other being a principle that is tied to the core of mankind's early innovative abilities but has long since been regarded as irrelevant.

The Building Circularity Indicator assessment model (Verberne, 2016) served as the foundation for this research and this research expanded upon this model. Step by step this can help to make the Circular Economy tangible and hopefully the standard economic model in the built environment. The Dutch government set a goal to be fully circular in 2050 (Ministry of infrastructure and the environment & Ministry of economic affairs, 2016) which is still a long time to go but I hope that this research has contributed towards achieving this ambitious goal.

I would like to thank all my colleagues at Alba Concepts who helped a lot during my graduation period with input, challenges to work on and even just by making work more fun during the time spent at the office. I especially like to thank my company supervisor, Stijn van Enckevort whom always made time to discuss about ideas, results or just to help with the process and the BCI team that constantly expands the expertise regarding the Circular Economy and the BCI, which lead to valuable insights and helped in making decisions.

I would like to thank my supervisors from the University of Technology Eindhoven, Qi Han whom helped me with my process during all the meetings and which helped in getting this report to where it is today. And Rijk Blok whom helped with the development of the building technology related ideas in this research.

Thanks to my friends that not only during my graduation but during my entire academic career made sure long days where alternated with long nights.

And last, but not least. Thanks to my parents and brother for always supporting me with everything I do and helping with anything I ask for.

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Summary

Ever since the industrial revolution, the use of coal as a fuel for energy production and the requirement of space for (heavy) industrial activity led to an increase of greenhouse gases into the atmosphere. (American Institute of Physics, 2017) This activity also required a step increase of delving raw materials, The exponential increase of all this producing, consuming and disposal of goods and emission of greenhouse gases lead to global warming. A lot of focus has been put on renewable energy to reduce emissions but our industrial economy has never evolved from a linear take-make-dispose pattern since this is established during the industrial revolution. (Ellen MacArthur Foundation, 2013)

The circular economy is a principle that synthesizes multiple schools of thought from sustainability and industrial engineering principles. (Ellen MacArthur Foundation, 2013) there are many different definitions but the principle consists of the biological cycle, the economic model and the technical cycle and seven principles to guide the circular economy concept (Ellen MacArthur Foundation, 2013; Schoolderman et al., 2014). Where the linear model stops at disposal, the circular economy model defines feedback loops where products and material circle back into the economy. (Ellen MacArthur Foundation, 2013) the circular economy does not only attempt to solve the problems caused by the linear economy, it is also estimated that the economic potential is worth billions. Making it a problem solver but also a (potential) money maker. This makes research towards the circular economy a relevant topic in today's society.

The construction industry is the cause of 32.7% of the total waste generation (International Energy Agency, 2015), it accounts for 31% of the total energy use (International Energy Agency, 2015) and produces 9% of the total greenhouse gas emissions (European Union, 2016). Therefore it is important to apply circular principles to the built environment to reduce this.

"For the circular economy to become a success, a simple measure of achievement is necessary as a first step towards fully integrated reporting. (Kok, Wurpel, & Ten Wolde, 2013) The Building Circularity Indicator (BCI) assessment (Verberne, 2016) model attempts to achieve this. It assesses how well the principles of the Circular Economy are implemented in a building project by translating them to Key Performance Indicators (KPI's). Essentially the circular potential is determined by two major KPI's, the material in- and output and the disassembly potential of products and materials.

The BCI is calculated in four steps. First the Material Circularity Indicator (MCI) is calculated for all products with the material in- and output and the technical lifecycle. Then the Product circularity Indicator for all products is calculated with the MCI and Disassembly Determining Factors (DDF's) (Durmisevic, 2006). The next step is to categorize all products by shearing layer of Brand (Brand, 1994) and use a normalizing factors like volume, weight, price, etc. to calculate the System Circularity Indicator (SCI) of all layers. And the last step is to calculate the Building Circularity Indicator with the SCI's and the level of importance.

This research identified several limitations of calculating the disassembly potential is the BCI assessment model. The goal of this research is to solve these limitations. For this the following research question is formulated. *"How can the disassembly potential of a building be*

determined as an integral part of building circularity and what influence does this have on the Building Circularity Indicator Assessment model?"

A literature study is conducted to understand what the role is of disassembly to enable the circular economy and to identify influencing factors. The following aspects are considered:

- Disassembly and circular economy guiding principles
- Disassembly and the relation with the theory of building levels
- Disassembly as an integral aspect in the building development process
- The role of disassembly on material reutilization and reusability.

Furthermore, twenty-five factors categorized as technical, process-based on financial factors (van Oppen, 2017) are identified that influence building disassembly from existing research. Not only the built environment but also other sectors like industrial engineering and automotive are considered. Adding all the factors in the BCI assessment model would make the model too complex. Therefore the decision is made to only incorporate the most important disassembly factors in the assessment model.

Two surveys are conducted with the Fuzzy Delphi Method (FDM) to validate and make a selection of disassembly factors and to determine the relative weights of the disassembly factors. A hypothesis is formulated that there is a difference between importance of the disassembly factors. This can be covered with assigning weights for disassembly factors in the BCI assessment model. From the results of the first survey twelve factors are selected and from the results of the second survey the weights are determined. By validating the impact of the weights no significant difference is found between the importance of disassembly factors. This does not support the hypothesis and the decision is made to use equal weights for disassembly factors in the BCI assessment model.

A new conceptual model for the BCI assessment model is developed to solve the limitations of the BCI assessment model. Disassembly factors are implemented in the model as technical requirements, preconditions and drivers. In the MCI step all products are classified according to a proposed method to determine building levels. In the PCI step, relational patterns based on detail drawings serve as framework to assess the Disassembly Potential of all products with the new disassembly factors. According to reusability of products or a Disassembly Potential threshold, systems are determined in the SCI step. These systems represent clusters of products that can be assessed for Disassembly Potential as an entity. Finally in the BCI step, all PCI's and SCI's are aggregated with a normalizing factor to determine one score to indicate the circular potential of a building.

The new BCI assessment model is validated with a case study of a building designed for disassembly. After a short validation session with the developers the resulting disassembly potential reflects their experience with assembling and disassembling their model house. Furthermore the results are compared with the old BCI assessment model. The difference seems bigger on lower building levels than higher building levels, which is expected, but more test cases are required to draw conclusions of the impact of the new calculation method on the score. It was impossible to determine disassembly potential in the old BCI assessment model without framework. Providing this is another big contribution of this research. By using relational patterns and detail drawings the BCI assessment model became more transparent. This method is also used to calculate the old BCI assessment model for the comparison.

Samenvatting

Sinds de industriële revolutie heeft het gebruik van steenkool als brandstof voor energieproductie en de behoefte aan ruimte voor (zware) industriële activiteiten voor een toename aan broeikasgassen in de atmosfeer gezorgd. (American Institute of Physics, 2017) Dit veroorzaakte ook een toenemende grondstofwinning. Deze exponentiele stijging van productie, consumptie, afval creatie en uitstoot van broeikasgassen leidt tot opwarming van de aarde. De grootste focus is gelegd op het toepassen en gebruiken van groene energie om emissies te verlagen, maar onze industriële economie is nooit verder geëvolueerd vanuit een "take-make-dispose" patroon sinds dit tot stand is gekomen tijdens de industriële evolutie.

De Circulaire Economie is een principe dat tot stand is gekomen door het combineren van meerdere denkrichtingen uit duurzame en industriële principes. (Ellen MacArthur Foundation, 2013) De Circulaire Economie bestaat uit de biologische cyclus, het economisch model, de technische cyclus en zeven principes om de circulaire economie te sturen. (Ellen MacArthur Foundation, 2013; Schoolderman et al., 2014) Waar het lineaire model stopt bij afval, definieert de circulaire economie "feedback loops" waardoor materialen en producten terug circuleren in de economie. (Ellen MacArthur Foundation, 2013) De circulaire economie helpt niet alleen bij het oplossen van de problemen veroorzaakt door de lineaire economie, het is ook ingeschat dat de economische potentie miljarden waar is. Dit maakt het niet alleen een probleem oplosser maar ook een (potentieel) verdienmodel. Dit maakt onderzoek naar de circulaire economie een relevant onderwerp in de hedendaagse samenleving.

De bouwindustrie is de veroorzaker van 32.7% van de totale afvalproductie, (International Energy Agency, 2015) 31% van het totale energiegebruik (International Energy Agency, 2015) en 9% van de totale emissie van broeikasgassen. (European Union, 2016) Daarom is het belangrijk om circulaire principes toe te passen in de gebouwde omgeving om dit te reduceren.

"Om de circulair economie een succes te laten worden, is een eenvoudig meetinstrument nodig als eerste stap naar integraal rapporteren." (Kok et al., 2013) de Building Circularity Indicator (BCI) beoordelingsmodel beoogd dit te bereiken. Het beoordeelt hoe goed de principes van de circulaire economie toegepast zijn in een bouwproject door deze te vertalen naar "Key Performance Indicators". In essentie wordt de circulaire potentie bepaald door twee belangrijke KPI's. Namelijk, materiaal in- en output en de losmaakbaarheid potentie van materialen en producten.

De BCI wordt bepaald in vier stappen. Eerst wordt de "Material Circularity Indicator" (MCI) berekend met de materiaal in- en output en de levensduur. Dan wordt de "Product Circularity Indicator" (PCI) berekend met de MCI en "Disassembly Determining Factors" (Durmisevic, 2006). De volgende stap is om alle producten te categoriseren onder de "shearing layers of Brand" (Brand, 1994) en om een normalisatiefactor te gebruiken om de "System Circularity Indicator" (SCI) te berekenen. Als laatst wordt de "Building Circularity Indicator" (BCI) berekend met de SCI's en het niveau van belangrijkheid van de lagen.

Beperkingen zijn geïdentificeerd voor het berekenen van de losmaakbaarheid potentie in het BCI beoordelingsmodel. Het doel van dit onderzoek is om deze op te lossen. De volgende onderzoeksvraag is geformuleerd. *"Hoe kan de losmaakbaarheid potentie van een gebouw*

bepaald worden als integraal onderdeel van circulair bouwen en wat is de invloed hiervan op het Building Circularity Indicator beoordelingsmodel?"

Een literatuuronderzoek is uitgevoerd om inzicht te krijgen in de rol van losmaakbaarheid om de circulaire economie mogelijk te maken en om beïnvloedende factoren te identificeren. De volgende aspecten zijn beschouwd:

- Losmaakbaarheid en circulaire economie sturende principes
- Losmaakbaarheid en de relatie met de theorie van gebouwniveaus.
- Losmaakbaarheid als integraal aspect in het gebouw ontwikkelproces
- De rol van losmaakbaarheid op materiaal hergebruik en herbruikbaarheid

Vijfentwintig factoren zijn geïdentificeerd uit bestaande onderzoeken, gecategoriseerd als technische, procesmatige en financiële factoren (van Oppen, 2017), die invloed hebben op losmaakbaarheid. Als al deze factoren worden toegepast in het boordelingsmodel wordt deze te complex. Daarom is gekozen om een selectie te maken van meest belangrijke factoren.

Twee enquête-onderzoeken zijn uitgevoerd met de "Fuzzy Delphi Methode" (FDM) om losmaakbaarheid factoren te selecteren en het gewicht te bepalen. Een hypothese is opgesteld dat er een verschil is tussen de mate van belangrijkheid van de losmaakbaarheid factoren. Dit kan meegenomen worden door gewichten te bepalen voor losmaakbaarheid factoren in het BCI beoordelingsmodel. De resultaten van de eerste enquête-ronde zijn gebruikt om twaalf factoren te selecteren en de resultaten van de tweede enquête-ronde zijn gebruikt om het gewicht te bepalen. Door de impact van het gewicht te valideren in het model is geen significant verschil gevonden voor de losmaakbaarheid factoren. Dit komt niet overeen met de hypothese maar de keuze is gemaakt om gelijke gewichten toe te passen.

Een nieuw conceptueel model is ontwikkeld om de beperkingen van het BCI beoordelingsmodel op te lossen. Losmaakbaarheid factoren zijn geïmplementeerd als technische factoren, precondities en drivers. In de MCI stap worden voor alle producten het gebouwniveau bepaald. In de PCI stap functioneren relatiepatronen, gebaseerd op detailtekeningen, als kader om de losmaakbaarheid potentie te beoordelen met de nieuwe losmaakbaarheid factoren. Aan de hand van herbruikbaarheid of een drempelwaarde voor losmaakbaarheid potentie worden systemen gedefinieerd. De systemen representeren clusters van producten die als geheel op losmaakbaarheid potentie beoordeeld kunnen worden. In de laatste stap wordt de BCI bepaald door de PCI's en SCI's samen te voegen met een normalisatiefactor. Dit geeft één score voor de circulaire potentie van een gebouw.

Het nieuwe BCI beoordelingsmodel is gevalideerd met een case study van een demontabel gebouw. De resultaten zijn in een korte sessie met de ontwerpers besproken en de resulterende losmaakbaarheid potentie van het gebouw komt overeen met de opgedane ervaring om de modelwoning in en uit elkaar te halen. De case study is beoordeeld met het oude en het nieuwe BCI model beoordelingsmodel en de resultaten zijn vergeleken. Het verschil tussen de resultaten lijkt groter bij een laag gebouwniveau. Meer test cases zijn nodig om te concluderen wat de impact is van de nieuwe berekeningsmethode van losmaakbaarheid op de score. Het was onmogelijk om in het oude beoordelingsmodel de losmaakbaarheid te bepalen zonder referentiekader. Dit is opgelost door relatiepatronen te bepalen aan de hand van detailtekeningen. Dit referentiekader is ook gebruikt om de oude methode te berekenen. Dit is een belangrijke toegevoegde waarde van dit onderzoek.

Abstract

The economy follows a linear take-make-waste pattern which leads to waste generation, depletion of the earth and global warming. The Circular Economy is a principle that aims to reduce this. It consists of the ecological feedback loop, the economy model and the technological feedback loop. Because the building industry is a major contributor to these problems it is important to enable a circular economy in the industry.

A simple measurement of achievement will help in making the circular economy a success. The Building Circularity Indicator (BCI) assessment model is a measurement tool to calculate the circular potential of a building. It is developed by translating circular principles to Key Performance Indicators (KPI's) and disassembly potential is an important KPI in the model.

In this research limitations are addressed for measuring the disassembly Potential of a building in the BCI. A literature research is conducted to what disassembly means for the circular economy and which factors influence disassembly. Twenty-five factors are identified.

A survey is conducted to identify and select the most important disassembly factors and to determine weights to implement these in the BCI assessment model. A conceptual model is built which aims to solve the limitation of measuring the disassembly potential. A framework based on relational patterns is used and disassembly potential is calculated for both products and systems in the BCI assessment model. Reusability is considered very important when determining the disassembly potential.

The model is validated with a case study of a building that is designed for disassembly and results are compared with the old BCI assessment model. This research brings the BCI assessment model one step further on the road to creating an all-inclusive model for building circularity. Recommendations based on limitations of this research are made and for further extension of the BCI assessment model.

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Glossary

4/6/10-R Model	Model describing all possible material reutilization strategies
BCI	Building Circularity Indicator
Bill of Disassembly Potential	List of the Product Disassembly Potential of all products and the Connection Disassembly Potential of all products
Bill of Materials	List of all materials and products in an assembly (building) with related properties
BOM	Bill of Materials
Building Circularity Indicator	Final score of the BCI assessment model, all results aggregated in one score
Building Circularity Indicator assessment model	Measurement tool to determine the circular potential of a building (development)
Building development process	The entire process from idea untill cycling material back into the economy or disposal
Building levels	Method to decompose a building in different scales. Not related to elevation levels
Circular Economy	Economy model with circular ecological and technical feedback loops
Detail drawing	Technical drawing (blueprint) of a junction in a building
DfA	Design for Adaptability
DfD	Design for Disassembly
Disassembly	Taking something apart
Disassembly Determining Factors	Factors to calculate the Transformation Capacity model (Durmisevic, 2006)
Disassembly Potential	The score between 0-1 of how possible it is to disassemble. 0 being the lowest and 1 being the highest
Drivers	Financial drivers stimulate the circular economy.
IPF-Model	Model by van Oppen (2017) defining Technisch Inhoudelijk (I), Proces (P) and Financieel-Economisch (F)
KPI	Key Performance Indicator
Linear Economy	Economy model following a take-make-disposal pattern
Material Circularity Indicator	Circular potential of material(s) of a product within a building
Material reutilization	Reusing materials in any way described by the 10-R model
MCI	Material Circularity Indicator
PCI	Product Circularity Indicator
Preconditions	Preconditions give organizations options to include in their procurement for which a building or process has to comply.
Product Circularity Indicator	Circular potential of a product within a building, MCI*DP
SCI	System Circularity Indicator
System Circularity Indicator	Circular potential of a system within a building
Technical requirements	Technical factors used to calculate the KPI's in the BCI assessment model

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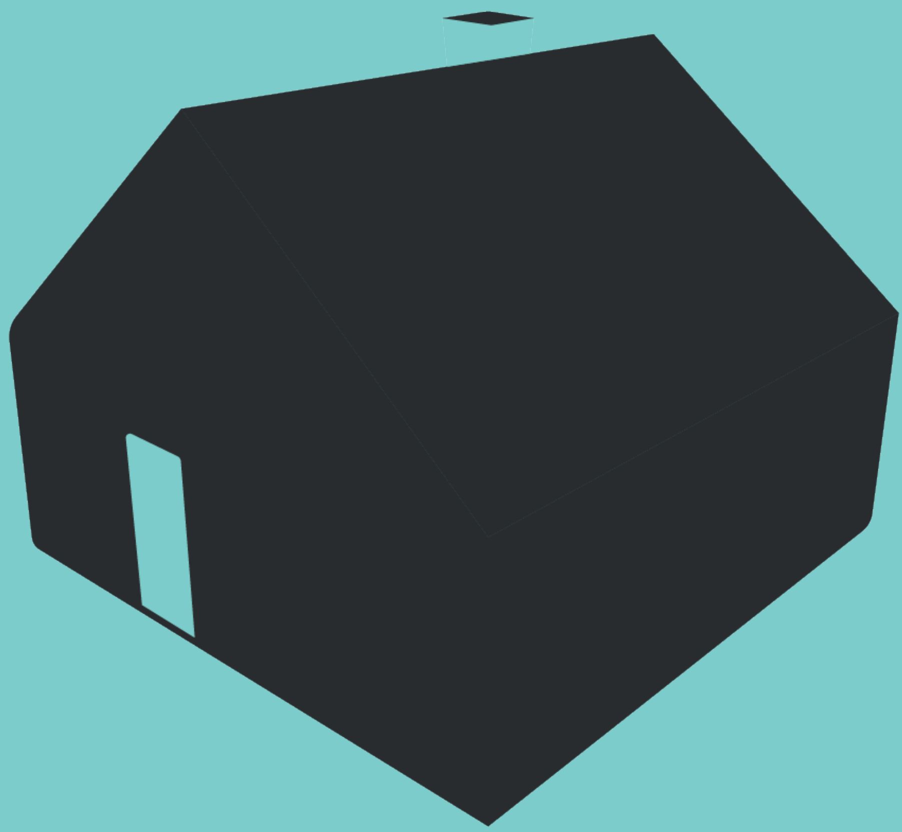

1

Introduction

We live in a take-make-dispose economy. A Circular Economy can help in reducing waste generation and raw material extraction. The building industry is a big contributor to these issues. The Building Circularity Indicator (BCI) assessment model aims to measure the circular potential of a building in which disassembly potentials plays a big role. This research aims to redevelop the method for assessing disassembly potential in the BCI assessment model.

In this chapter the outline of the research is set. Starting with a description of the problem context and the problem definition which set a base to determine the research questions. The relevance describes the scientific and societal contribution of this research and the research design explains the methodology used to answer the research questions. This chapter is closed with a reading guide that explains the structure of this thesis.

1.1. Research context

Reducing the use of fossil fuels and with that the emissions of greenhouse gases is evident to preserve our planet, looking at for instance the Paris Agreement (UNFCCC. Conference of the Parties (COP), 2015). A less discussed issue is however (projected) material scarcity. In the European Union a total of 2509.9 million ton waste was produced in 2014 and a large percentage of this is lost as landfill or burned to never be replenished again by the earth. (Eurostat, 2014) Material scarcity will become an issue in the future and is a result from the linear take-make-dispose pattern of our economic model. A solution would be reshaping our economic structure to a circular economy. A circular economy enables feedback loops where materials are collected and reinserted back into the economy (Ellen MacArthur Foundation, 2013). We are far away from operating in a circular economy and this is also the case for the built environment. The built environment is one of the biggest contributors of waste (International Energy Agency, 2015) so transitioning towards a circular economy is very important.

For the circular economy to become a success, a simple measure of achievement will be needed, as a first step towards fully integrated reporting. (Kok, Wurpel, & Ten Wolde, 2013). The Building Circularity Indicator (BCI) is an assessment model that aims to capture the circularity potential of building developments. It provide guidance during the decision making process to concretize the circular ambition of different stakeholders. (Verberne, 2016) The BCI is based on Key Performance Indicators (KPI's) These KPI's are structured as technical requirements, Preconditions and Drivers (Verberne, 2016). Disassembly is one of the two major KPI's in the BCI assessment model and is an important factor to enable material reutilization.

Since the industrial revolution we have started to develop more and more complex materials and products. The focus is put on assembly and not on disassembly. This has not always been the case, historically disassembly was just as important. (Lambert & Gupta, 2005) The first buildings were likely made with sticks and leaves, before settlement in one location became apparent. (Crowther, 1999b) With the ability to settle down and the development of new technologies, adding more luxury to buildings became possible and disassembly was not necessary anymore. (Lambert & Gupta, 2005) The result of this development is that buildings nowadays are too complex and products are too interconnected with each other to be disassembled in a proper way. Demolishment using bulldozers is the common practice because it is easier, faster and cheaper. (Crowther, 1999b)

1.2. Problem definition

The BCI assessment model is the first model that aims to measure the circular potential of a building by translating circular principles (Ellen MacArthur Foundation, 2013) into Key Performance Indicators (KPI's). One of these KPI's is disassembly possibilities of a building and this determines fifty percent of the score of the BCI. A simple measurement of achievement is necessary for integrated reporting and will stimulate the transition to a circular economy. (Kok et al., 2013)

Disassembly is a difficult principle to assess. Some guidelines exists to Design for Disassembly and guidelines exist (Ciarimboli & Guy, 2005; Durmisevic, 2006; Thormark, 2001) The BCI is the first comprehensive model to assess sustainability principles in the form of the circular economy in an integral way. However assumptions regarding disassembly are made during the development of the BCI and these assumptions have to be verified. This also leads to limitations in the BCI assessment model.

A solid framework to assess disassembly potential is missing in the BCI assessment model. This influences the transparency of the results when assessing the disassembly potential, leading to ambiguity in results. Furthermore it is unknown whether the factors incorporated in the BCI assessment model are the most important to assess the disassembly potential. The Ellen MacArthur Foundations stimulates thinking in 'systems' and while disassembly is integrated to calculate the PCI, it is not to calculate the SCI. This disregards how parts influence one another within a whole.

Because disassembly has such a big influence in the BCI assessment model, these limitations affect how well the model performs in calculating the circular potential. By redeveloping the calculation method for disassembly potential, these limitations can be solved.

1.3. Research questions

The method for assessing the disassembly key performance indicator (KPI) is redeveloped in this research. A research is conducted to identify what disassembly means for the circular economy in the built environment and what the limitations are in the BCI compared to this. The goal is to solve these limitations.

A hypothesis is formulated that there is a difference between the importance of disassembly factors. First disassembly factors are identified from literature and these are tested for relative importance to test this hypothesis. A conceptual model is developed to implement the principles of disassembly integrally in the BCI assessment model. To do this, the following research questions are formulated.

How can the disassembly potential of a building be determined as an integral part of building circularity and what influence does this have on the Building Circularity Indicator assessment model?

This research question will be answered in parts by answering the following sub-questions.

1. *Why is building disassembly important to enable the circular economy?*
2. *Which factors influence disassembly potential of buildings in the entire building development process?*
3. *Which disassembly factors have to be included in the new BCI assessment model to determine the disassembly potential of a building?*
4. *What is the relative importance (weight) of the disassembly factors that can be implemented in the new BCI assessment model?*
5. *How can the decomposition of building levels be used to determine on which level the building can be disassembled?*
6. *Which method can be used assess the disassembly potential in the Building Circularity Indicator assessment model?*

7. *How can the assessment of building disassembly potential be integrally incorporated in the BCI assessment model?*

1.4. Research Design

This research combines quantitative and qualitative research methods to answer the research question and the sub-questions in four steps.

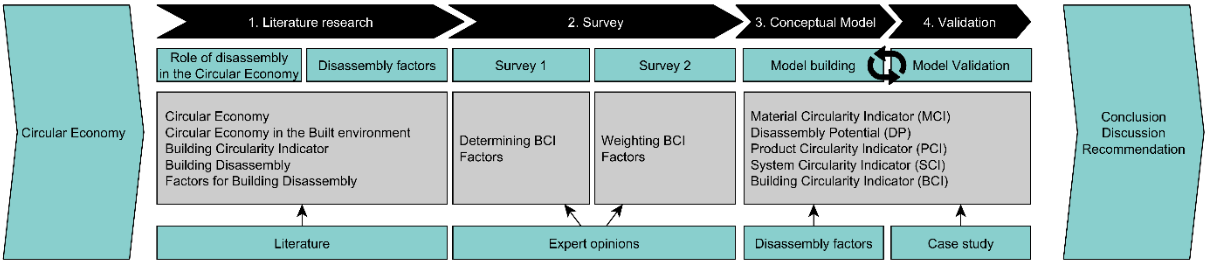

Figure 1: Research Design

First a literature research is executed. The literature review first explores what the principle of the circular economy is and what part disassembly of building materials plays in this. This used to determine which limitations are present and provides a base to redevelop the BCI assessment model.

Then the factors that previous researchers find important to enable disassembly are identified and explained. Identifying literature is not limited to the built environment but also other sectors where disassembly is more prevalent like industrial engineering and automotive engineering. This will answer research questions 1 and 2. These factors are then validated and assessed in the next step.

A survey is carried out among experts in the field, working in multiple phases of the building development process from initiative to demolishment/deconstruction, to validate and to determine the relative importance of the identified factors for disassembly. This is done in two survey round. The first is to validate the factors and to make a selection of the most important factors for disassembly. This answers research question 3.

A hypothesis is formulated that there is a difference between the importance of disassembly factors. The second survey round is performed to weight the relative importance. Both surveys are analyzed with the Fuzzy Delphi Method (Klir & Yuan, 1995). This is done to answer research question 4.

The results of aforementioned steps are applied to create a conceptual model to assess building disassembly in the new Building Circularity Indicator assessment model. The original Building Circularity Indicator will be changed and this will impact the calculation method. A case study is both used as iterative process to develop the assessment model and to validate the model in the next step. Therefore this is a preliminary result for research questions 5, 6 and 7.

A case study is used to aid the development of the assessment model and to validate the results. A building which is designed to be disassembled is assessed according to the new BCI assessment model and the old model which will help to understand the impact of the new calculation method on the score. This will definitively answer the research questions 5, 6 and

7. Limitations, assumptions and questions raised that are out of the scope of this research are discussed in the final discussion of the model.

The sub-questions help in defining the conclusion on the main research question. The final result is the conceptual model for the new BCI assessment model. A reflection is made to the scientific and societal relevance of this research and recommendations are made for further research.

1.5. Relevance of the research

It is estimated that 32.7% of the total waste generation is caused by the construction industry. Furthermore this industry accounts for about 31% of the total energy use (International Energy Agency, 2015) and 9% of the greenhouse gas emission (European Union, 2016). Research towards the circular economy in the built environment can help shifting away from a linear economy and will reduce waste and raw material extraction. There are many obstacles to overcome to truly achieve a circular economy but making a theoretical principle more practical will help to achieve a more sustainable society.

For the circular economy to become a success, a simple measure of achievement will be needed, as a first step towards fully integrated reporting. (Kok, Wurpel, & Ten Wolde, 2013) The BCI (Verberne, 2016) is the first attempt towards measuring the circular potential of buildings. Recommendations have been made to for further research. This research takes on an essential part which is the assessment of disassembly potential. Not many measurement tools for the circular potential of a building exist and by refining the model, the road to a common understanding of what the circular economy is in the building industry is paved. There are still more subjects to address because the principle of the circular economy is elaborate but every step helps to shift from a linear to a circular economy.

1.6. Reading guide

The second chapter of this research is a literature research towards the circular economy, the role of disassembly in the circular economy and what the limitations are of assessing disassembly potential in the current BCI. Then factors that influence disassembly in the building industry are identified and described. These are used to determine which factors will be implemented in the new BCI assessment model in the next chapter.

The third chapter describes the results of the survey to validate the disassembly factors, determine which factors should be included in the new BCI assessment model and to determine the relative weights of the disassembly factors.

The fourth chapter explains the new conceptual model for the BCI and how this is developed. It closes with a case study to validate the model.

In the fifth chapter the conclusions are drawn by relating the results back to the research questions. This chapter also includes a reflection on scientific and societal relevance and recommendations for further research based on the findings in this research.

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2

Disassembly of buildings to enable the Circular Economy

This chapter entails the literature research towards the role of disassembly in the circular economy and which factors influence whether a building can and will be disassembled instead of demolished. First an explanation is given of how the principle of the circular economy came into existence, why this is important and how it works.

Then the relation to the Building Circularity Indicator (BCI) assessment model is made. This is a tool to assess the circular potential of a building. Limitations are identified for assessing the disassembly potential in the model. These limitations are used to redevelop the building disassembly assessment model later in this research.

This chapter concludes with an overview of all identified factors that influence disassembly potential of buildings according to existing research. These are categorized as technical, process-based and financial-based factors. This provides a method to implement them in the BCI assessment model later in this research. In the next chapter a selection of these factors is made to implement in the model and the relative weight is determined.

2.1. Sustainable development

"Sustainability is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs". (United Nations World Commission on Environment and Development, 1987)

This is a quote from the Brundtland report which popularized and defined the term of sustainable development and is regarded as a leading report for the road of developing a more sustainable world, preserving our planet. But why do we need sustainable development and what does this mean? The atmosphere naturally contains an amount of greenhouse gases, These gases absorb and emit radiant energy within the thermal infrared range. The primary present gases are water vapor (H2O), Carbon dioxide (CO2), methane (CH4), Nitrous oxide (N2O), Ozone (O3), Chloro- and Hydrofluorocarbons (CFCs, HCFCs, etc). Ever since the first industrial revolution (1800-1870) the use of coal as a fuel for energy production and the requirement of space for (heavy) industrial activity led to an increase of greenhouse gases emitted into the atmosphere. (American Institute of Physics, 2017)

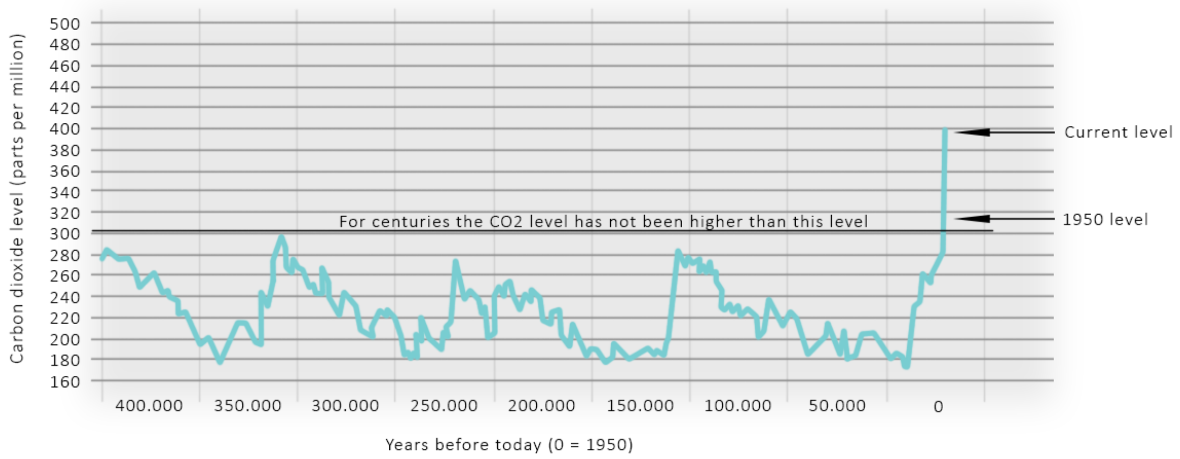

Figure 2: Carbon dioxide level for the past 400.000 years

The industrial activities also required a steep increase of delving raw materials from the earth to keep up with the production of goods. This exponential increase of producing, consuming and disposal of goods and emission of greenhouse gases leads to global warming. The effects of global warming are an increasing sea level because the arctic pole ice is melting, more extreme weather conditions, dirtier air, more acidic oceans, the extinction of species and more. (IPCC, 2007) This is the reason we require sustainable development. In the early days sustainable development has been adopted within three pillars namely environment, social and economic, also described as the triple-bottom line. (Elkington, 1998)

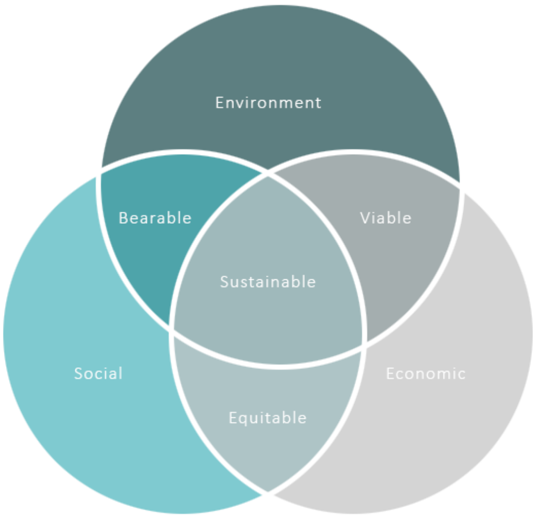

Figure 3: Sustainable development or also called Triple-bottom line model (Elkington, 1998)

Sustainability knows many aspects and a heavy focus has been put on energy production. Because burning fossil fuels directly releases greenhouse gasses and other harmful substances into the atmosphere. New alternatives like solar panels, wind turbines and geothermal energy and others have been developed and are now widely used. The final share of renewable energy in the European Union in 2016 is approximately 17.0%. (Eurostat, 2017)

This is however not the only source of the problem. Raw materials are mined from the earth and processed into products. Delving the materials, producing goods and transportation also adds to the global emissions. Furthermore, raw material can only be mined once and once depleted will not grow back. In the European Union a total of 2509.9 million ton waste was produced in 2014. A major part of this was regarded to be large mineral waste from the mineral extraction and building and demolition industries. From this total sum almost 47% goes to landfill, 10% to backfill and about 37% is recycled. The rest is burned (Eurostat, 2014). Landfill has an impact on the earth through pollution of the environment and emission of methane (NH4). (El-Fadel, Findikakis, & Leckie, 1997).

As briefly mentioned above, a major part of the waste generation is the result of the construction and demolition sector and the mineral extraction sector. It is estimated that 32.7% of the total waste generation is caused by the construction industry. Furthermore this industry accounts for about 31% of the total energy use (International Energy Agency, 2015) and 9% of the greenhouse gas emission (European Union, 2016) Therefore it is very important that the building industry becomes more sustainable to decrease this. We have regulations regarding the energy use of buildings in the Netherlands called the EPC (Energie Prestatie Coefficient) and regarding the embodied Carbon dioxide (CO2) called the MPG (Milieu Prestatie Gebouw). Multiple independent green building certificates exist like BREEAM and LEED to label buildings based on the sustainability performance of the building. (Cole & Valdebenito, 2013)

2.2. Linear Economy

Our industrial economy has never evolved from the fundamental characteristic: the linear model of resource consumption that follow the take-make-dispose pattern. (Ellen MacArthur Foundation, 2013) Since the industrial revolution there was no need for another model. Virgin materials were cheap and seemed immeasurably vast. (McDonough, W., & Braungart, 2002) This however led to the disposal of products in landfill sites with all the environmental damage that this has caused. Furthermore, as stated before, the mineral extraction industry itself causes for a lot of large mineral waste. (Eurostat, 2014)

Figure 4: The Linear Economy model

The other issue is the depletion of virgin materials from the extraction and disposal of these materials. Although it is still widely regarded that use of virgin materials is still cheaper than the costs involved with reusing or recycling materials, the commodity price index shown in the report by the Ellen McArthur foundation (2013) suggests a change in price trend for the future.

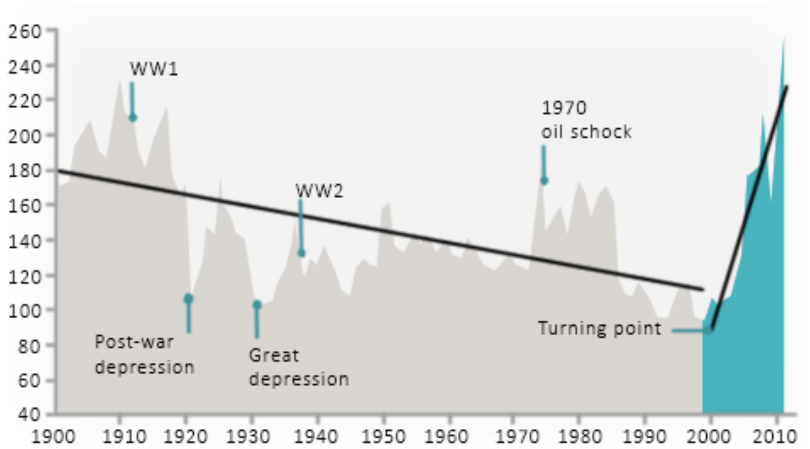

Figure 5: Commodity price index of the last century as cited by Ellen McArthur Foundation (2013, p.18)

The commodity prices have risen steeply in the last decade and this seems to be the start of an irreversible process. This leads to a decline in economic growth which is bad for business and eventually for the welfare of people. A transition is necessary to a new economic structure that moves away from traditional practices, just like reusing and recycling moves away from traditional non-renewable materials as input. A proposed model that supports this is called the circular economy (CE). (Ellen MacArthur Foundation, 2013) The concept of circular economy is relatively new and has gained a substantial amount of attention since the report by the Ellen MacArthur Foundation (2013).

2.3. Circular Economy

The circular economy refers to an industrial economy that is restorative by intention; aims to rely on renewable energy; minimizes, tracks, and eliminates the use of toxic chemicals; and eradicates waste through careful design. (Ellen MacArthur Foundation, 2013) the principle is developed by synthesizing multiple schools of thought from the following sustainability and industrial engineering principles. (Ellen MacArthur Foundation, 2013)

- Regenerative design (Lyle, 1970)
- Performance economy (Stahel, 1976)
- Cradle to Cradle (McDonough, W., & Braungart, 2002)
- Industrial Ecology (Frosch, 1992)
- Biomimicry (Benyus, 2002)

As the name of the principle already gives away is that it is based on "circular" feedback loops in the economic model to achieve the restorative intention. The principle of cradle-to-cradle (McDonough, W., & Braungart, 2002) defines an ecological loop and a technical loop that is adopted by the CE principle.

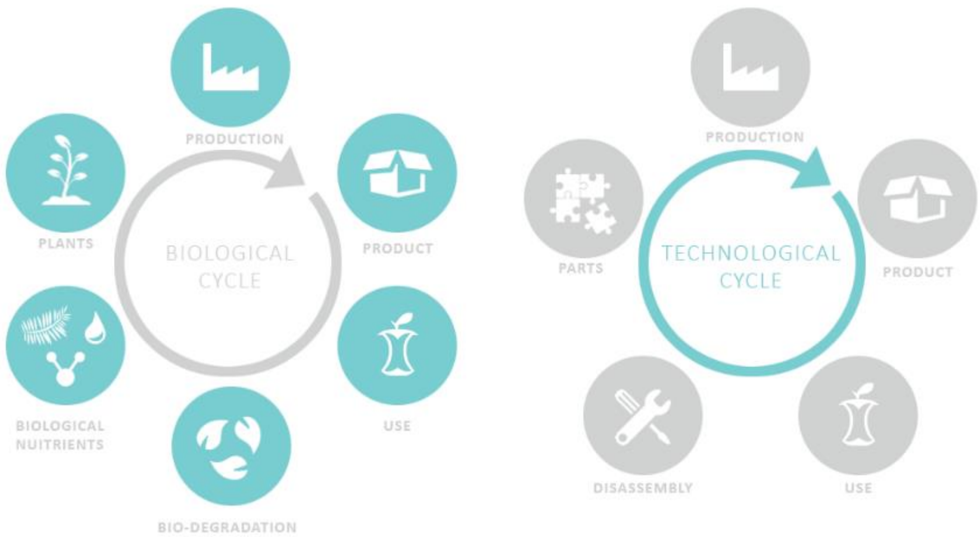

Figure 6: Cradle to Cradle (William McDonough & Michael Braungart, 2002)

The principle of a circular economy by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013) is adopted in this research because it combines the for mentioned principles and because it provides a framework for further research on the individual aspects and to combine them. Even though there are many different definitions for the Circular Economy, the definition (and the extensions) by the Ellen MacArthur Foundation is used the most. (Kirchherr, Reike, & Hekkert, 2017). The model distinguishes three integrated parts. The biological cycle, the economic model and the technical cycle. Where the linear economy stops at disposal, the circular model defines feedback loops where consumed products circle back into the economy model through different loops. (Ellen MacArthur Foundation, 2013) see Figure 7.

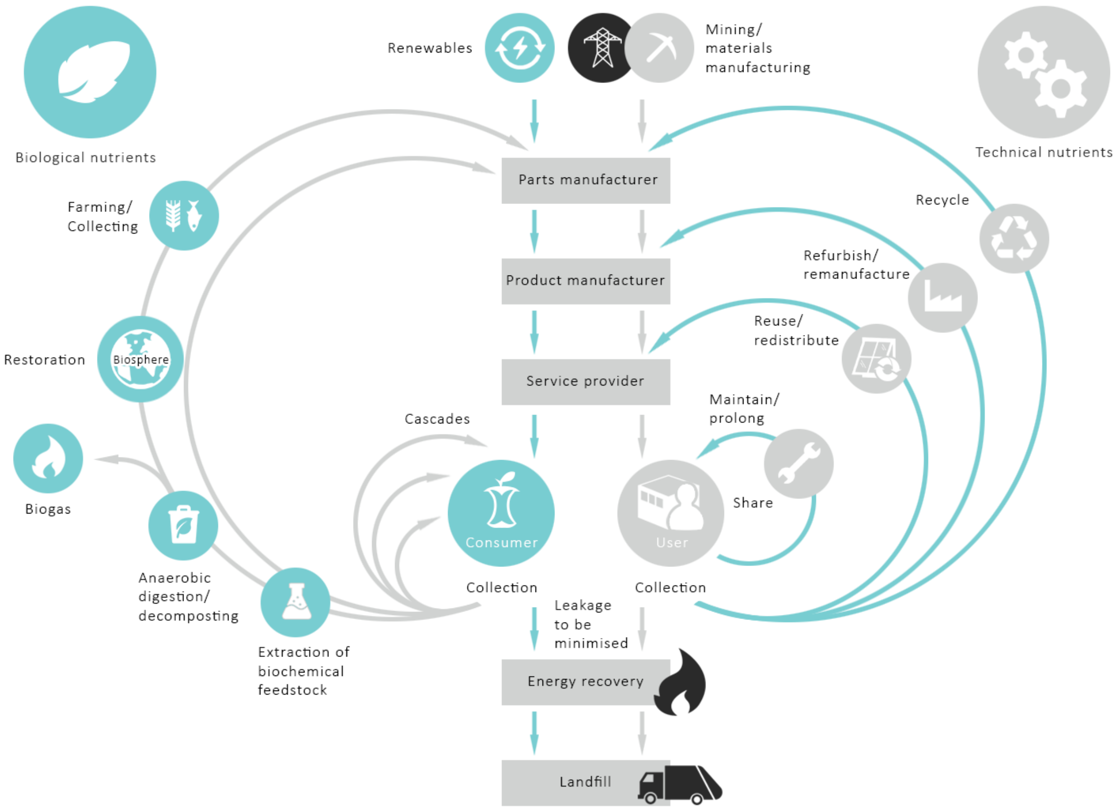

Figure 7: The Circular Economy model (Ellen MacArthur Foundation, 2013)

The center of the circular economy model represents the economy with as starting point the manufacturing of materials, parts and product. These become available on the market and are used or consumed. Instead of just disposing the product at the end of the lifecycle, products are to be collected to enter one of the many feedback loops. Leakage of materials to be burned for energy recovery or as landfill should be minimized. (Ellen MacArthur Foundation, 2013) Internal business processes during production or service provision should also include this principle where abundant material should be minimized or reused, recycled, etc. which means the principle can be applied to different scales (refuse, rethink, reduce). The economic potential estimated by the Ellen MacArthur Foundation is a saving of 380-630 billion dollars, just by looking at a subset of manufacturing sectors in the European Union (Ellen MacArthur Foundation, 2013) Grasping this potential requires new business models and revenue models.

The left side of the model represents the biological cycle. Materials that can safely be returned to the biosphere can function as biological nutrients for the next cycle. There is still a cycle to go through with this principle to keep the soil in a high quality state. (McDonough, W., & Braungart, 2002) The way of disposing of these products is crucial. When it ends up as landfill or burned it does not contribute as a biological nutrient, which still happens most of the time. In fact it will harm the ecosphere because of the saturation of nutrients. (El-Fadel et al., 1997)

The right side of the model represents the technical cycle. It aims to minimize the use of raw materials by extending the lifetime of products, thus needing less materials through smart design or by reutilizing the materials through different ways. Several levels of material reutilization are possible and displayed in the model. The smallest loop is to maintain the usage of materials. The longest loop is to recycle. Smaller loops are preferred over longer loops because they tend to require less energy and produce less residual waste. Different levels of material reutilization require different strategies on how to handle them. (Ellen MacArthur Foundation, 2013)

The following principles are set to guide the circular economy concept by Ellen MacArthur. (Ellen MacArthur Foundation, 2013)

- Design out waste: waste does not exist when the biological and technical components (or 'nutrients') of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and refurbishment.
- Build resilience through diversity: modularity, versatility, and adaptively are prized features that need to be prioritized in an uncertain and fast-evolving world.
- Rely on energy from renewable sources: systems should ultimately aim to run on renewable sources.
- Think in 'systems': the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts is crucial.
- Waste is food: on the biological nutrient side, the ability to reintroduce products and materials back into the biosphere and on the technical nutrient side improvements in quality.

Two more principles were added in follow up research by Schoolderman et al. (Schoolderman et al., 2014)

- The bio based approach: biological materials will be used in an increasing extend.
- Entrepreneurship as base: the circular economy will revolve around new revenue models and partnerships.

2.4. Circular Economy in the Built Environment

About 50% of the raw materials used in the Netherlands are designated for the construction sector (Schoolderman et al., 2014) while material prices are rising due to material scarcity (Ellen MacArthur Foundation, 2013). The construction sector is also a major contributor to the generation of waste, about 31.7% of all the waste generated in the world is originated from the construction sector. The Dutch government set a goal to be fully circular in 2050 (Ministry of infrastructure and the environment & Ministry of economic affairs, 2016) which will be a challenge.

The transition to a circular building sector is therefore important and received many attention by scholars, businesses and government instances. (Carra & Magdani, 2017; Ministry of infrastructure and the environment & Ministry of economic affairs, 2016; Ness & Xing, 2017; Schut, Crielaard, & Mesman, 2015). Applying the principles of a circular economy (Ellen MacArthur Foundation, 2013; Schoolderman et al., 2014) will help this. A model is developed where these principles are fit to the built environment. (Cheshire, 2016) (Figure 8)

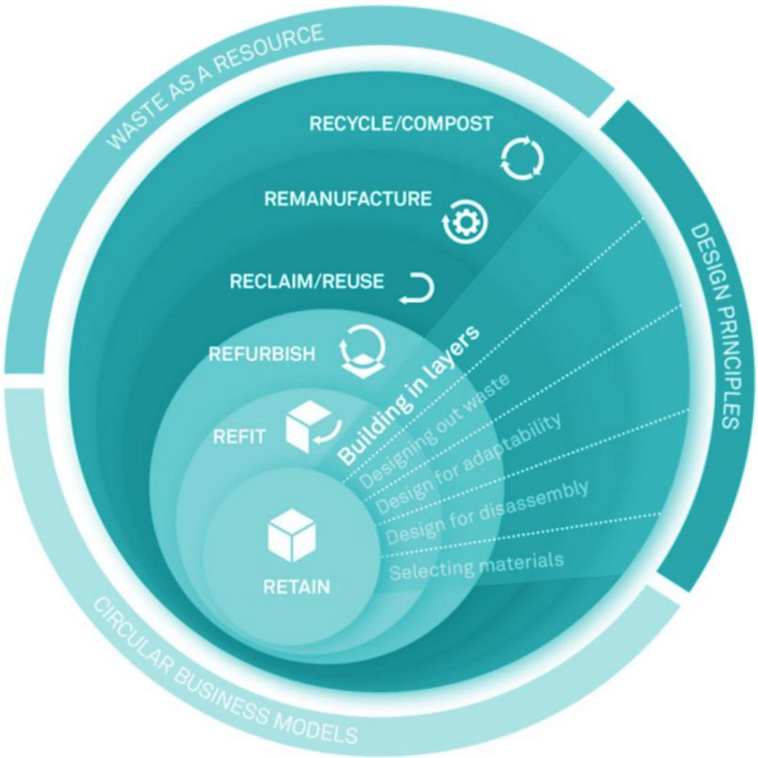

Figure 8: Applying Circular Economy principles to the Built Environment (Cheshire, 2016)

The concentric circles represent the technical and biological loop and consists of the different levels of material reutilization as mentioned before (Retain, Refit, Refurbish, Reclaim/reuse, Remanufacture, Recycle/compost) where inner circles (Retain, Refit, Refurbish) are the most desirable because it is the most resource-efficient. Design principles for buildings are overlaid as method to achieve this. Consisting of;

- Building in Layers (Brand, 1994)
- Design-out waste
- Design for adaptability
- Design for disassembly
- Selecting materials

The surrounding circles represent how new business model help enable to achieve a more circular economy across the construction sector. (Cheshire, 2016) The design principles for circular building aim to make conscious decisions regarding several aspects of circularity. They all have a focus on different areas and should be used in combination when designing a building.

2.4.1. Building in layers (Brand, 1994)

The shearing layers of change are proposed by Brand (1994) and are adopted in various technologic research regarding end of life assessment of buildings. In his research different layers are distinguished from stuff, space plan, services, skin, structure and site. Based on the assumption that these layers have different life cycles, design decisions can be made regarding their end of life scenarios. The structure has a longer lifetime in a building than the stuff, which results that during the entire lifecycle of the building, some components need to be replaced more frequently than other components. (Brand, 1994)

Figure 9: Shearing layers of change (Brand, 1994)

2.4.2. Design out of waste

Design out of waste is a principle developed to reduce waste during the entire building development process, but is mostly focused on the engineering side. There are five key principles that define design out of waste which are:

- Design for reuse and recovery
- Design for off-site construction
- Design for materials optimization
- Design for waste efficient procurement; and
- Design for deconstruction and Flexibility

Applying these principles will result in less waste during and at the end of the lifecycle in a building. (WRAP UK, 2009) Clearly the principles of different levels to reutilize components (Cheshire, 2016) are reflected in these principles.

2.4.3. Design for Adaptability

Design for Adaptability is a design principle first introduced in the industrial engineering. The principle explains that design efforts usually look at the life cycle costs to reduce waste and pollution, but is limited regarding looking to extend the life cycle. Adaptable systems are designed to modify performance of the building or building parts to enable a longer useful life. An adaptable building is therefore able to easily evolve together with shifting user requirements, increasing the potential use lifecycle. (Kasarda et al., 2007)

2.4.4. Design for Disassembly

Design for Disassembly intends to maximize materials conservations from building end-of-life management by making parts possible to be disassembled, replaces and/or reused, and create adaptable buildings to avoid building removals altogether. Furthermore, just like the principle of Design for Adaptability, it is a strategy to deal with the inability of buildings to remain useful (changing requirements). Furthermore it aims to discourage the destructive demolition and disposal of buildings. (Ciarimboli & Guy, 2005)

2.4.5. Selecting materials

The materials used in a building are an important factor when building for the circular economy. There are many different properties to consider when selecting the materials. A research towards assessment criteria for sustainable building material selection identified twenty-four different performance criteria which are grouped in six categories. (Akadiri & Olomolaiye, 2013) To select materials for the circular economy, the reusable in- and output is important.

2.4.6. Measuring the Circular Economy

"For the circular economy to become a success, a simple measure of achievement is necessary as a first step towards fully integrated reporting. This allows organizations (companies, harbors, governments, investors) to give incentives to their (chain) partners to become more circular, e.g. in procurement processes. In addition, governments can support frontrunning companies with tax or subsidies measures based on the index. It will also provide first insights in true value creation throughout the value chain" (Kok, Wurpel, & Ten Wolde, 2013). To measure the circular potential of a building, Key Performance Indicators (KPI's) based on the principles for a circular economy mentioned in paragraph 2.4 have to be defined.

A couple studies are conducted towards measuring circularity in the building sector. The Ellen macArthur Foundation developed an approach to measure material circularity (Ellen MacArthur Foundation & Granta Design, 2015). This measurement tool is focused on all material usage in the world. The circular measurement method should incorporate the principles for a circular economy to guide the circular economy concept (Cheshire, 2016; Ellen MacArthur Foundation, 2013)

The Building Circularity Indicator assessment model is developed specifically for the construction sector and identified the KPI's for circular economy in the built environment. (Verberne, 2016) This model is developed at the University of Technology Eindhoven and is the first model to integrate disassembly as a major KPI for circularity. Therefore this model is adopted in this research.

2.5. Building Circularity Indicator (BCI) assessment model

The Building Circularity Indicator is an assessment model that is developed by adopting the basis of the material circularity indicator (Ellen MacArthur Foundation & Granta Design, 2015) the model aims to provide guidance during the decision making process to concretize the circular ambition of different stakeholders. (Verberne, 2016)

The Building Circularity Indicator is a step towards measuring of how well the principles of the circular economy are implemented in a building project. It is important to note that this model limits itself to technical factors and not the underlying process. New business models and revenue models are required to support the decisions made in the BCI.

the basis of this model consists of several KPI's that are identified from literature and experts. (Verberne, 2016) These KPI's are technical requirements, drivers or preconditions. Only technical requirements are incorporated in the calculation model. The preconditions and drivers serve to give principals the possibility to include their interests even better. (Verberne, 2016) Table 1 shows the KPI's that are included in the BCI assessment model.

Table 1: KPI's for building circularity (Verberne, 2016)

Technical Requirement	Preconditions	Drivers
Type of input & Type of output (6R-model)	Material health/toxicity	Material scarcity
Technical lifetime	CO2-footprint/emissions	Potential financial value
Disassembly possibilities (6S-model)	Renewable energy usage	Future reuse possibilities (second-hand market)
Cycles (technological & biological)	Environmental impact	

The BCI is calculated in four steps starting by calculating the Material Circularity Indicator (MCI), then the Product Circularity Indicator (PCI), then the System Circularity Indicator (SCI) and lastly the Building Circularity Indicator (BCI). In Appendix 1 the calculation methods are explained. All indicators result in factorial scores between 1 (fully circular) and 0 (fully linear). The conceptual model is displayed in Figure 10.

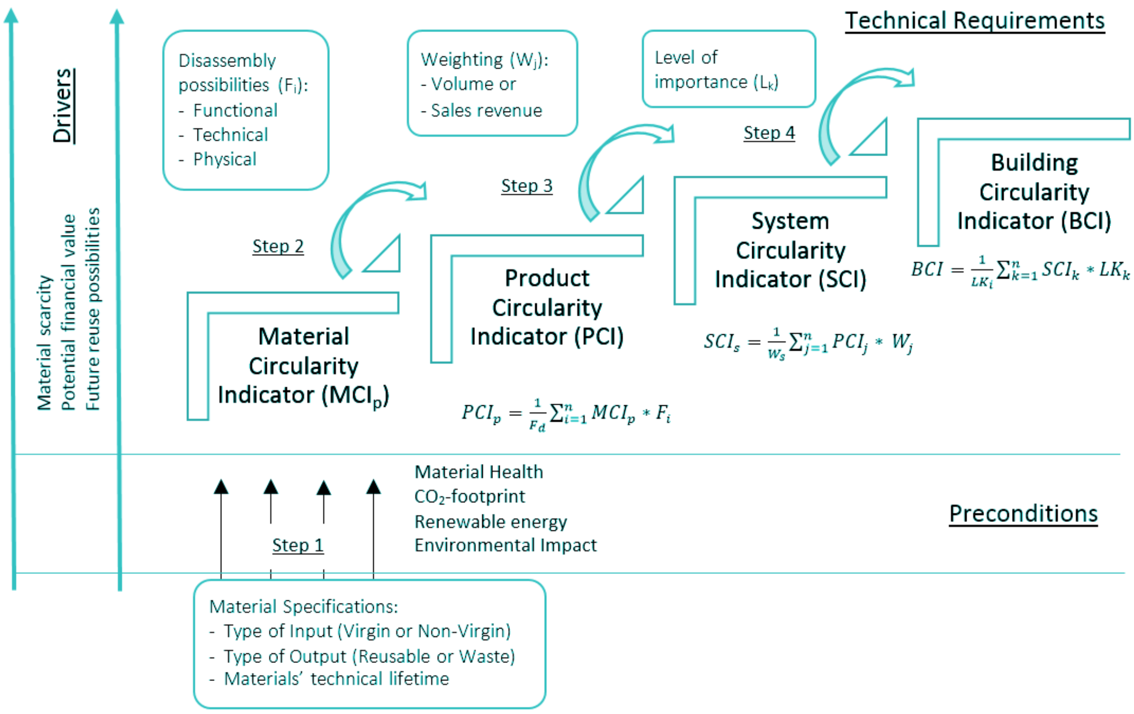

Figure 10: Building Circularity Indicator conceptual model (Verberne, 2016)

The steps how to calculate the BCI are explained following paragraphs. Followed up by an overview of project assessed in practice with the BCI assessment model.

2.5.1. Material Circularity Indicator (MCI)

The MCI is calculated with the percentage of material input (virgin/non virgin), the material output (energy recovery/landfill) and the technical lifecycle. This represents the theoretical circular potential of each product. A Bill of Materials (BOM) is used as input to calculate the MCI of every product (Verberne, 2016). The MCI represents fifty percent of the circular potential of products.

2.5.2. Product Circularity Indicator (PCI)

The PCI is calculated with the MCI and the disassembly possibilities of each products. The disassembly possibilities of products are assessed with seven Disassembly Determining Factors (DDF's) adopted from the Transformation Capacity model (Durmisevic, 2006).

Seven DDF's are selected to keep the BCI model evident to assess the disassembly possibilities. (Verberne, 2016) All disassembly factors are weighted equally important in the assessment model.

The BOM is used to determine the disassembly score for each factor. (Verberne, 2016) The score of each disassembly factor for each product is estimated. The disassembly possibility represents the other fifty percent of the circular potential of products.

2.5.3. System Circularity Indicator (SCI)

The System Circularity Indicator is an aggregation of all MCI_p (theoretical) and PCI_p (practical) towards a systematic value. (Verberne, 2016) The PCI's are categorized according to the different layers of Brand (Brand, 1994) resulting in a value for the System Circularity Indicators (SCI) for each layer.

Normalized factors are used to determine a weighted average of each product towards the SCI. The factor mass is chosen. This factor is disputable and other proposals are also arguable like sales revenue, number of materials, volume, etc. (Verberne, 2016)

Alba Concepts disregarded the SCI and adopted the Element Circularity Indicator (ECI). (Appendix 5) First of all the PCI's are categorized according to their disassembly potential. When two or more products cannot be disassembled from each other, they are considered a system. The assessment is done by using the factor “accessibility to connection”. Every product is assessed whether the connections are accessible. When due to inaccessibility, damage has to be inflicted to the product or surroundings and this is more than twenty percent of the build costs, two (or more) products form a system.

2.5.4. Building Circularity Indicator (BCI)

The Building Circularity Indicator functions to aggregate all results into one score corrected by the level of importance. The level of importance is based on the layers of Brand (Brand, 1994) because products with a shorter lifetime are considered more important to be circular than products with a shorter lifetime. (Verberne, 2016) The BCI determines the overall performance of a building according to circular potential and can be used to compare the circular potential of buildings with each other

2.6. Building disassembly

Since the industrial revolution we have started to develop more and more complex materials and products. The focus is put on assembly and not on disassembly. This has not always been the case, historically disassembly was just as important. (Lambert & Gupta, 2005) The first buildings were likely made with sticks and leaves, before settlement in one location became apparent. (Crowther, 1999b) With the ability to settle down and the development of new technologies, adding more luxury to buildings became possible and disassembly was not necessary anymore. (Lambert & Gupta, 2005) The result of this development is that buildings nowadays are too complex and products are too interconnected with each other to be disassembled in a proper way. Demolishment using bulldozers is the common practice because it is easier, faster and cheaper. (Crowther, 1999b)

Even though this is the case, there are examples of projects that are developed with deconstruction in mind. These can be found in more historic but also in more modern buildings. The principle is called Design for Disassembly (DfD) and is an adoption from the industrial engineering sector (life cycle engineering). The intention is to reutilize materials. (Soh, Ong, & Nee, 2014) Disassembly is an enabler of the technical feedback loop of the circular economy. The goal of this loop is to keep materials in the economy that are otherwise lost forever. Reusing building materials can be done in different ways. (Cheshire, 2016)

2.6.1. Disassembly and Circular Economy

Three principles of the Circular Economy can be directly related to disassembly of buildings.

"Design out waste: waste does not exist when the biological and technical components (or 'nutrients') of a product are designed by intention to fit within a biological or technical materials cycle, designed for disassembly and refurbishment." (Ellen MacArthur Foundation, 2013)

To enable the technical feedback loops for building material realization, products have to be disassembled from buildings. In accordance, the building materials should be reusable to be able to apply them again in new situations, whether this is in a building application or other applications.

"Build resilience through diversity: modularity, versatility, and adaptively are prized features that need to be prioritized in an uncertain and fast-evolving world." (Ellen MacArthur Foundation, 2013)

Enabling disassembly of buildings will make these buildings more adaptive. Material can be disassembled and replaced when they do not meet the requirements anymore. This will make maintenance easier and prolong the lifecycles of buildings.

"Think in 'systems': the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts is crucial."(Ellen MacArthur Foundation, 2013)

A building is a complex system of different building materials that are interconnected with each other, being able to understand the relations between products will make it possible to understand how disassembly of products or systems affect other parts of the building.

2.6.2. Disassembly and building levels

The physical decomposition levels (Durmisevic, 2006) define different building levels that can be used to compare products of different scales with each other. Products on a lower building level together form a product on a higher building level and so on. Disassembly is possible on all scales. Figure 11 shows a theoretical example of totally fixed structure, a partially open and a fully open structure. The left figure shows everything fixed together. The middle figure shows a combination of products fixed together on different building levels which may be possible to disassemble as a whole, and products on lower levels that can be disassembled individually. The right figure shows that all products are possible to disassemble individually.

The goal for the circular economy in to reutilize materials and there are different strategies. In general, the tighter the circles are, the larger the savings should be in the embedded costs in terms of material, labor, energy, capital and of the associated rucksack of externalities (Ellen MacArthur Foundation, 2013) When a product is reused as an entity in a new building, this is a smaller circular process than disassembling everything to recycle and make new products. When a product is reutilized through multiple circular processes, at some point it will be used up. At this point recycling, energy recovery or landfill will be the only option. A true circular product can iterate through different circular processes during its lifetime and is then recycled for new product manufacture.

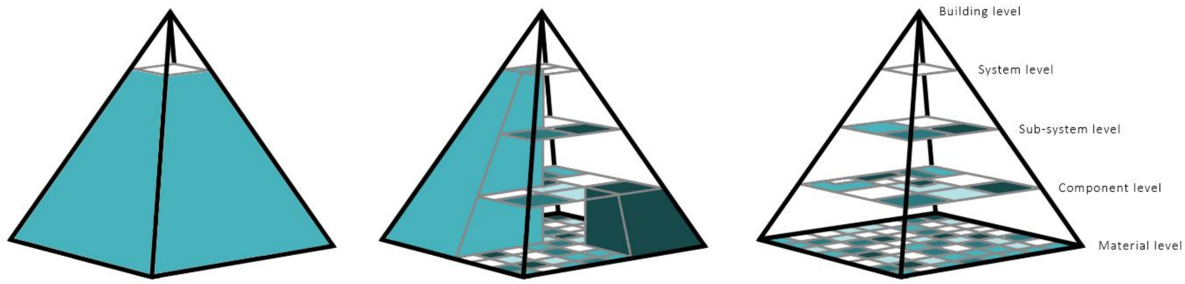

Figure 11: Fixed, partially fixed and open structure on different building levels (Durmisevic, 2006)

The material reutilization strategies are compared to the building levels of the BCI (Verberne, 2016) and the physical decomposition levels (Durmisevic, 2006) This research considers disassembly for retain, refit, refurbish, reclaim/reuse and remanufacture. This means that recycling is disregarded as disassembly is not the most important factor to enable recycling but the technical limitations to recycling are a more important obstacle for different products to overcome. (Schneider & Ragossnig, 2014)

Table 2: Material reutilization strategies compared to physical decomposition levels

<table>
<tr><th></th><th>Ladder van Lansink (Lansink, 1979)</th><th>Circular Economy (Cheshire, 2016)</th><th>Physical composition (Durmisevic, 2006)</th><th>Building Circularity Indicator (Verberne, 2016)</th></tr>
<tr><td rowspan="6">Circular Economy</td><td rowspan="2">Prevention</td><td>Retain</td><td rowspan="5">Building level
System level
Sub-System level
Component level</td><td rowspan="5">Building level
System level
Product level</td></tr>
<tr><td>Refit</td></tr>
<tr><td rowspan="3">Reuse</td><td>Refurbish</td></tr>
<tr><td>Reclaim/reuse</td></tr>
<tr><td>Remanufacture</td></tr>
<tr><td>Recycle</td><td>Recycle/compost</td><td rowspan="4">Material level</td><td rowspan="4">Material level</td></tr>
<tr><td rowspan="3">Linear Economy</td><td>Energy recovery</td><td rowspan="2">Energy recovery</td></tr>
<tr><td>Incineration</td></tr>
<tr><td>Landfill</td><td>Landfill</td></tr>
</table>

2.6.3. Disassembly as integral principle in the building development process

Design for Disassembly (DfD) is a design principle for buildings to facilitate future change and the eventual dismantlement (in part or as whole) for recovery of systems, components, and materials. (Ciarimboli & Guy, 2005) Extensive research has been conducted to principles, factors and guides for DfD and the influence of DfD to deconstruct a building at the end of the lifecycle instead of demolish. The Disassembly Determining Factors (Durmisevic, 2006) assess disassembly potential on the functional, technical and physical domain. By applying an integrated system design process, the design constantly improves with each decision-making cycle. (Durmisevic, 2006)

When the design aspects for DfD are properly integrated it is more likely that a building will be deconstructed instead of demolished. However the process of a building development is extensive. This is not captured by only considering Design for Disassembly. A deconstruction process requires changes to the progress of construction methods, process and planning. (Rios, Chong, & Grau, 2015) so it is important that disassembly principles are adopted integrally in the entire building development process.

To determine which factors are important for disassembly, all phases of the building development process have to be considered. A study to integrating circular principles in the real estate development process defines different phases of a real estate development process. (Scherer, 2016) (Table 3). These phases will be used in this research in chapter 0 to determine the target audience for a survey to determine the relative importance between disassembly factors.

Table 3: Building Development phases and examples of stakeholders, adaption from Scherer (2016)

Building Development Phase	Examples of stakeholders
Preparation (includes initiative and design)	Clients
	Architects
	Consultants
	Real estate developer
	Project developer
	Specialized engineers
Realisation	Contractor
	Specialized engineers
	Project managers
	Sub-contractors
	Supplyers
Exploitation	Future user
	Clients
	Maintenance planner
	Maintenance contractor
Deconstruction	Demolishment contractor
	Material resellers
	Clients
	Hazardous material removers
	Supplyers

Van Oppen (2017) states that circular economy is achieved by looking at the technical side, the process and the finances of a building development process. This is captured in the IPF-model (van Oppen, 2017).

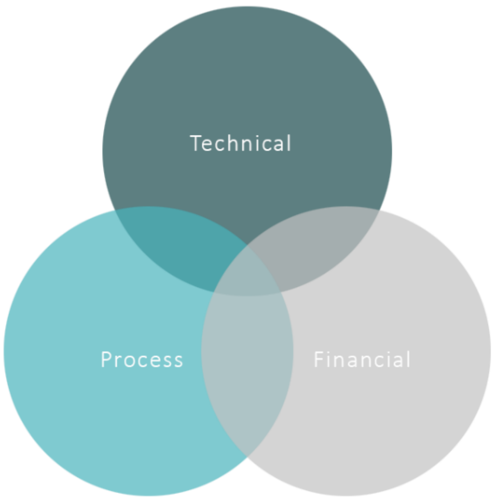

Figure 12: IPF-model (van Oppen, 2017) for enabling the Circular Economy.

By categorizing factors that enable disassembly they can be included integrally in the BCI assessment model. In chapter 2.5 is mentioned that KPI's for circularity in the BCI assessment model consist of technical requirements, preconditions and drivers. The following method to include disassembly factors in the BCI model is used.

- Technical disassembly factors are used in the BCI to calculate the circular potential.

- Process based disassembly factors are included as preconditions to give organizations options to include in their procurement for which a building or process has to comply.
- Financial based factors are included as driver. The economy is financially driven and will stimulate the transition to a circular economy.

2.6.4. Disassembly and material reutilization

The goal of disassembling building components is to reuse them. There are more factors that influence whether a component is suitable for reuse. (Hobbs & Adams, 2017; Lambert & Gupta, 2005) It is however important to note that when a material or product can be disassembled, it is not necessarily reusable or recyclable. Because this research is focused on the disassembly potential as one of the factors that enable material reutilization, the rest of the factors are not considered and therefore no further research is done to identify which factors influence reusability.

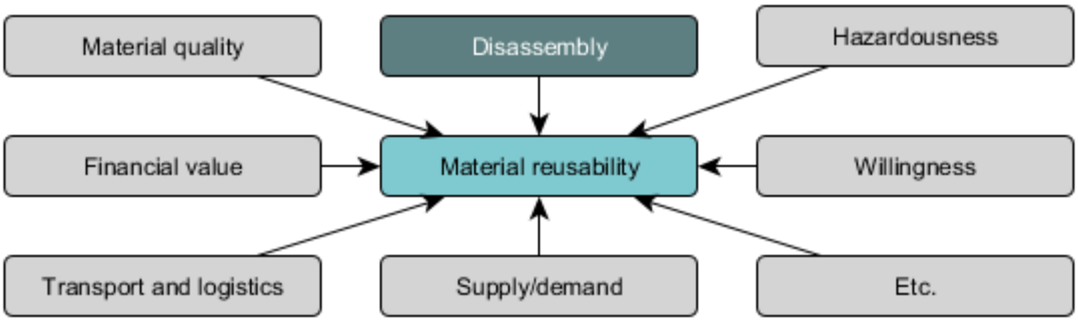

Figure 13: Disassembly as factor for material reutilization. (Hobbs & Adams, 2017)

Disassembly can be done for different ways of material reutilization. These are mentioned in model for a circular economy in the built environment. (Cheshire, 2016) The first step of being more efficient with resources is to reduce the amount of resources that are necessary, keeping materials in the building for as long as possible makes disassembly unnecessary. On a higher level, products remain intact as much as possible and are reused in a different application. (Cheshire, 2016) On a lower level, recycling brings a product back (with a recycling process) to the original raw materials. These raw materials are then used to make new products.

2.6.5. Limitations of measuring Disassembly Potential in the BCI

The BOM of a project is used to determine the input for the MCI and the PCI. There is no requirement for the level of detail of the BOM based on building levels. The principle of building levels is also widely used in Building Information Modelling (BIM). BIM is a settled principle in the building industry and the level of detail (also comparable to building levels) defines how detailed the BIM model is. There are still practical implications regarding standards and compatibility of different sub-sectors in the built environment, making lower levels of detail difficult to apply to projects. (Hijazi & Omar, 2017) Therefore, requiring a specific building level as input for the BOM would lead to practical problems where data is not sufficiently standardized and therefore available. This would make it difficult to calculate the BCI for every project.

Regarding assessing disassembly potential, this does create an inconsistency in the BCI assessment model. According to the physical decomposition levels (Durmisevic, 2006) different levels exist in a building. A higher building level is made up of an assembly of products on a lower building level. This does not only influence the material reutilization strategies, which are different compared to different physical decomposition levels (chapter 2.6.4, Table 2) But this also leads to comparing the disassembly potential of products of different levels with each other.

The issue with measuring disassembly is that traditional models based on correlation co-efficiency have a high level of imprecision when dealing with linguistic data (Durmisevic, 2006). Because disassembly is difficult to measure precisely it is recommended to use fuzzy type of variables to measure disassembly. This also brings a factor of subjectivity in the assessment model. The disassembly potential is determined from the BOM. Disassembly is about relations and from a BOM it is difficult to make a comprehensive assessment. A more accurate evaluation process is recommended.

The introduction of more Disassembly Determining Factors (DDF) is recommended (Verberne, 2016). The variables included in the BCI are only a selection of the Disassembly Determining Factors. (Durmisevic, 2006) The selection process for the variables that are included in the BCI is unclear and therefore it is unknown whether the most important factors are included. Additionally the TC variables are based on the design phase of a building. A deconstruction process requires changes to the progress of construction methods, process and planning. (Rios et al., 2015) therefore it is interesting to research whether an integrated view of disassembly into the entire building development process is necessary. This leads to a broader scope of disassembly factors.

Another limitation of the BCI is that the BCI regards disassembly as an intermediate step between the Material Circularity Indicator (MCI) and the Product Circularity Indicator (PCI). Durmisevic (2006) however argues for a system's way of thinking. Systems are composed of (sub-)assemblies based on functional (Brand, 1994) or physical decompositions (Durmisevic, 2006) It can be argued that this top-down approach is also preferred in the BCI. This requires to rethink how disassembly is incorporated in the BCI.

The goal of disassembly is material reutilization. It is difficult to relate back which products are reusable when they are grouped together in systems categorized by the shearing layers of Brand. (Brand, 1994)

2.7. Identifying factors for Building Disassembly

The goal is to identify factors that have an influence in the entire building development process to implement in the Building Circularity Indicator. An explorative method to find a comprehensive overview of disassembly in the building industry is applied. The next step of the research will be to validate these factors. Not all factors can be implemented in the BCI because this will make it too difficult to use, so the essence will be included after an analysis of the validation in chapter 3.2. Less important factors are disregarded and therefore an explorative research to find out the factors is sufficient. The Disassembly Determining Factors (DDF's) that determine the Transformation Capacity (Durmisevic, 2006) will function as a starting point (Table 4) to which additional factors are identified. The bold factors in this table are included in the BCI assessment model (Verberne, 2016)

Table 4: Transformation Capacity (Durmisevic, 2006) Bold factors are adopted in the BCI (verberne, 2016)

Transformation Capacity (TC)			
Independence	Functional decomposition	Functional decomposition	**Functiona separation**
			Functional dependence
		Systematisation	Structure of material levels
			Type of clustering
	Technical decomposition	Base elements	Type of base element
		Life Cycle Coordination	Use life cycle coordination
			Technical life cycle coordination
			Coordination of life cycles and size
		Relational pattern	Type of relational pattern
Exchangability	Physical decomposition	Assembly process	Assembly direction
			Assembly sequences
		Geometry	**Geometry of product edge**
			Standardisation of product edge
		Connections	**Type of connections**
			Accessibility to fixings
			Tolerance
			Morphology of joints

As described in chapter 2.5.2, the disassembly factors included in the BCI (Verberne, 2016) are based on the main categories Functional, Technical and Physical Decomposition. (Durmisevic, 2006) this research aims to keep these major categories represented in the new BCI assessment model when determining which disassembly factors are incorporated.

Explanations of the factors and what the influence is on disassembly are gathered in a comparison table. Based on this an overview of each factor and their influence is described. The factors are categorized as technical, process-based and financial-based. The literature consulted is not limited to the building engineering sector but also considers the industrial engineering and automotive sector because disassembly is more common in these industries. A relation with the literature from the building engineering sector is always identified. In total eighteen research have been consulted.

Twenty five disassembly factors are identified that influence disassembly in the entire building development process. A relation is made with the IPF-model (van Oppen, 2017) the following factors are identified.

Table 5: Factors that influence disassembly categorized as technical, process-based and financial-based factors.

Technical disassembly factors	Process-based disassembly factors	Financial-based disassembly factors
Functional separation	Coding and marking	Disassembly costs
Independency	Disassembly instructions	Disassembly time
Structure of material levels	User participation	
Type of base element	Disassembler Expertise	
Technical/use life cycle coordination	Number of operations	
Ease of handling	Deconstruction safety	
Type of relational pattern		
Assembly direction based on assembly type		
Assembly sequence		
Assembly shape		
Method of fabrication		
Type of connection		
Accessibility to connection		
Tolerance between components		
Amount of fasteners		
Hazardousness of materials		
Required tools		

The following chapters give an overview of the factors and an explanation of the factors.

2.7.1. Technical Disassembly Factors

Design for Disassembly (DfD) is the design of buildings to facilitate change and eventual dismantlement. This includes developing the assemblies, components, materials, construction techniques and information and management systems (Ciarimboli & Guy, 2005). This definition already mentions that process (information and management system) and finance (maximize economic value) is already important in Design for Disassembly. technological factors are the factors that influence the design and design decisions, which includes assemblies, materials and the building methodology. The Disassembly Determining Factors (Durmisevic, 2006) are technological factors. Additional research expands on these factors and immediately functions as a second validation. An overview of all identified technological factors is shown in Table 6.

Table 6: Technical factors for disassembly

Disassembly factor	Times mentioned in literature
Functional separation	9
Independency	5
Structure of material levels	8
Type of base element	1
Technical/use life cycle coordination	1
Ease of handling	5
Type of relational pattern	5
Assembly direction based on assembly type	2
Assembly sequence	5

Assembly shape	1
Method of fabrication	5
Type of connection	12
Accessibility to connection	9
Tolerance between components	2
Amount of fasteners	7
Hazardousness of materials	5
Required tools	7

2.7.1.1. Functional separation

A building is composed of different materials and products that fulfill specific functions. The type of functions can be very generally categorized or very specific. The layers of Brand (Brand, 1994) are an example of functions on a more general level and these can be differentiated further. For example the function "skin" consist of the function "insulation", among other things. Functional separation describes that a product or assembly should not have multiple functions in a building. This can be interpreted more global like separating structure, enclosure and services (Ciarimboli & Guy, 2005; Crowther, 1999; SenterNovem, 2007) or more specific by separating functions as much as possible (de Ridder, 2011; Dowie & Simon, 1994; Durmisevic, 2006; Hassanain & Harkness, 1997; Wang, Liu, Ong, & Nee, 2014) When one specific function does not meet the user requirements anymore, this can be disassembled separately. It is on one hand a waste to remove a product that fulfills multiple functions and underperforms for one of this. On the other hand a product is more likely to be possible to disassemble when it fulfills one function. Separation of functions is guaranteed by the choice of building methodology and for this reason it is considered a technological factor. These decisions are made primarily during the design phase.

2.7.1.2. Independency

Independency is an adaption of the factor functional dependence (Durmisevic, 2006). Decoupling components is desirable (Hassanain & Harkness, 1997) but when systems are grouped this should be done as much according to functional and physical interactivity as possible (Wang et al., 2014). Incorporation and interpenetration of different components lead to dependency which influences the integrity of components (Durmisevic, 2006). Disassembly is aimed to reuse and when the integrity is compromised due to disassembly, it can be said that the disassembly potential is less. (Ciarimboli & Guy, 2005). This is also an issue in the industrial engineering but on a complex level of products. (Dowie & Simon, 1994) during the design, interpenetration of different products and incorporation of components together in build ups should be avoided, securing independency. This is dependent on the chosen building methodology and therefore a technological factor.

2.7.1.3. Structure of material levels

Minimizing the amount of products makes disassembly easier (Crowther, 1999; Dowie & Simon, 1994; Hassanain & Harkness, 1997; Soh, Ong, & Nee, 2014; Thormark, 2002; Wang et al., 2014). The greater the number of building parts integrated into one component, the fewer physical connections needed on site. (Durmisevic, 2006) A building methodology can be chosen that either incorporates multiple products in one assembly, making it a higher building level or assembling all individual products on sit and is therefore a technological factor.

2.7.1.4. Type of clustering

Type of clustering defines for which specifications are used to group building products in an assembly or into a product of a higher level. It is possible to group them by function; which relates back to independency and function separation, by lifecycle; which relates back to technical/functional lifecycle coordination, or differently. (Durmisevic, 2006). In the industrial engineering the value of the (raw) material is determinant to group products. (Lambert & Gupta, 2005; Peiró, Ardente, & Mathieux, 2017) so these are easier extracted and reused. Depending on the type of clustering, disassembly can be made easier because when either the lifetime is over or the function does not meet the requirement anymore, the total cluster of products can be disassembled rather than individual parts. It is possible to determine whether this is taken into account or not when designing assemblies or choosing products.

2.7.1.5. Type of base element

Independency (2.7.1.2) can be guaranteed by specifying base elements to connect products or clusters of product together. A base element can act as intermediary without compromising the products when disassembly is undertaken. (Durmisevic, 2006) A base element can be anything when it is designed to be easy to disassemble. Careful design of detail drawings is required to create connections with or without base element.

2.7.1.6. Technical/use life cycle coordination

A distinction is usually made between technical lifetime and usable lifetime. A product can be technically in a good condition, but not meet the functional requirements anymore and vice versa. Lifecycle coordination means that element with a long lifecycle should be assembled first and disassembled last. (Crowther, 1999; Durmisevic, 2006; Wang et al., 2014) type of clustering (chapter 2.7.1.4) defines how components are grouped and life cycle coordination what the sequence of assembly is for these groups. (Durmisevic, 2006)

2.7.1.7. Life cycle related to size / ease of handling

Smaller sized components are easier to disassemble than larger scale components due to ease of handling. (Ciarimboli & Guy, 2005; Crowther, 1999; Durmisevic, 2006) This lesson is also learnt from the principle of Industrieel Flexibel en demontabel bouwen (IFD) (SenterNovem, 2007) the reusable components were too big (de Ridder, 2011) which makes it difficult to disassemble and to reuse. When designing products or clusters of products, attention has to be paid to limit the size.

2.7.1.8. Type of relational pattern

A relational pattern represents how products and parts are connected with each other. Open systems have a vertical and hierarchical relational pattern. This allows for isolation and separation of products and enables change through disassembly. (Crowther, 1999; Peiró et al., 2017) The number of relations is very important for the disassembly potential. (Durmisevic, 2006) More relations lead to closed assemblies. The relational pattern is dependent on the building method and therefore is considered a technological factor.

2.7.1.9. Assembly direction based on assembly type

The assembly sequence sets a mirror image for the disassembly sequence. (Durmisevic, 2006) if everything is assembled sequential on each other, there is only one direction to disassemble. sequencing should be planned as such that parallel disassembly is possible. (Crowther, 1999) this creates multiple angles to disassemble and therefore makes it easier and quicker to disassemble. Careful planning of the assembly sequences in relation to components is required during the design process to make this possible.

2.7.1.10. Assembly sequence

Most researchers combine disassembly sequencing with disassembly direction. Durmisevic (Durmisevic, 2006) argues a differentiation where lower component levels should follow up on higher component levels during assembly. Because the assembly sequence determines in which sequence should be disassembled. (Hassanain & Harkness, 1997; Lambert & Gupta, 2005) In product design assembly sequencing is used to split mechanical and electrical components. (Thormark, 2001) and it is a determinant factor to decrease disassembly time (Peeters, Vanegas, Dewulf, & Duflou, 2012) It is easier to take out smaller products. When components of the same level are connected with each other, it rules out relations with other building levels which makes disassembly harder.

2.7.1.11. Assembly shape

Assembly shape is an adoption of the factor geometry of product edge. The geometry of product boundaries (shape) can lead to open or interpenetrating geometry. This is influenced by interface design and the specification of the connection type. (Durmisevic, 2006) which is why it is a technological factor.

2.7.1.12. Method of fabrication

Method of fabrication is an adoption of the factor standardization of product edge. The method of fabrication describes whether a product or assembly is prefabricated or build on the construction site. (Durmisevic, 2006) Beside making the products more reusable, (Akanbi et al., 2018) prefabrication leads to easier disassembly due to standardization of connections (Durmisevic, 2006), easier accessible connections (Rios et al., 2015) and the ability to disassemble complete components on-site and further separation of components off-site. (Ciarimboli & Guy, 2005) The choice of building methodology and product selection decides the method of fabrication and is therefore considered a technological factor.

2.7.1.13. Type of connection

The type of connection is the most mentioned factor for disassembly and is essential to making disassembly possible. The design of connections is the last aspect for design for disassembly and is therefore a technological factor. There are typically three main types of connections. Direct, indirect and filled (Durmisevic, 2006) adhesives are generally considered bad for disassembly (Akanbi et al., 2018; Crowther, 1999; Dowie & Simon, 1994; Durmisevic, 2006; Peiró et al., 2017; Rios et al., 2015; Thormark, 2001) while mechanical connections are good. (Akanbi et al., 2018; Ciarimboli & Guy, 2005; Crowther, 1999; Durmisevic, 2006; Rios et al., 2015; Thormark, 2001) The industrial engineering also considers active connections which can be triggered to let loose. (Soh et al., 2014) this is not applied much in the building industry but could lead to the design of connections that are easier to disassemble than current traditional methods.

2.7.1.14. Accessibility to connections

Accessibility to connections refers to physically being able to access the connections between products without demolishing (parts) of the product. (Durmisevic, 2006) This influences the reusability of the product and surrounding products, but also makes the dismantling process easier and quicker. (Ciarimboli & Guy, 2005; Peeters et al., 2012; Rios et al., 2015; Soh et al., 2014; Thormark, 2001). During the design, attention has to be paid to the location of the connections and the assembly sequence to provide access which makes it a technological factor.

2.7.1.15. Tolerance between components

Tolerance means leaving space between components so they can be physically separated from each other (Durmisevic, 2006) This will also minimize the need for destructive methods. (Ciarimboli & Guy, 2005) Tolerance is usually designed to account for variance in the product measurements but designing tolerance can therefore also lead to easier disassembly.

2.7.1.16. Amount of fasteners

The amount of fasteners used should be minimized to ease disassembly and decrease disassembly time. (Ciarimboli & Guy, 2005; Crowther, 1999; Dowie & Simon, 1994; Peeters et al., 2012; Peiró et al., 2017; Soh et al., 2014; Thormark, 2001) The amount of fasteners is mainly determined by the structural integrity of the connection. Design of connections can influence the required fasteners.

2.7.1.17. Hazardousness of materials

Hazardous materials influence the time required to disassemble them and influence the disassembly process. (Ciarimboli & Guy, 2005; Dowie & Simon, 1994; Rios et al., 2015) Hazardous materials cannot be reused which decreases financial incentive. (Akanbi et al., 2018; Dowie & Simon, 1994) Designers should refrain from choosing hazardous materials when selecting products/materials.

2.7.1.18. Required tools

The required tools necessary to disassemble products can range from common hand tools to complex specialized tools (Crowther, 1999; Peiró et al., 2017; Thormark, 2001). This influences the ease of disassembly because tool changing costs time which is a big influence in disassembly in the industrial engineering. (Dowie & Simon, 1994; Peeters et al., 2012; Peiró et al., 2017; Soh et al., 2014) Other disassembly factors may influence the required tools like the type of connection and the accessibility to the connections and is therefore dependent on the design.

2.7.2. Process based disassembly factors

A process is a series of actions or operations conducing to an end. (Merriam-Webster, 2018) the building development process needs to be described as a parallel process representing the iterative process of real estate development. A high degree of complexity is recognized due to more stakeholders, faster changing market circumstances, an earlier participation of the future owner or user and changed laws and regulations.(Scherer, 2016). Factor that influence the process do not influence the building methodology or the design but by applying these factors integrally in the building development process they can help to make disassembly easier. Six process-based disassembly factors are identified.

Table 7: Process-based factors for disassembly

Disassembly factor	Times mentioned in literature
Coding and marking	6
Disassembly instructions	5
User participation	3
Disassembler expertise	4
Number of operations	4
Deconstruction safety	3

2.7.2.1. Coding and marking

Coding and marking means the labeling of materials and connections. This will ease identification and simplify the sorting and recycling process (Peeters et al., 2012; Thormark, 2001) Documentation of this is necessary during the entire building development process. labeling of connections and materials in the specifications all contribute to efficient disassembly and deconstruction. (Ciarimboli & Guy, 2005) and is therefore considered a process-based disassembly factor. Coding and marking can be facilitated by implementing product identification technologies in products as mentioned in the industrial engineering literature. (Vanegas et al., 2017) The manufacturer of building materials can code and mark their products and the contractor has to warrant this during the construction phase.

2.7.2.2. Disassembly instructions

Information is needed regarding the used materials and the assembly techniques applied in a construction. (Thormark, 2001) Instructions can make the process of deconstruction easier. (Ciarimboli & Guy, 2005; Peiró et al., 2017; Rios et al., 2015; Soh et al., 2014) Good documentation is required throughout the entire building development process, including changes during its lifetime (Thormark, 2001), so information is stored. It is considered a process-based factor because it does not influence the building methodology or choice of products but is about building information. As-built drawings (Ciarimboli & Guy, 2005; Rios et al., 2015) and disassembly instructions can be made available after the construction is finished and therefore is regarded as most important for the construction phase.

2.7.2.3. User participation

Involving the end-user or owner of the building in the process will help to prevent maintenance decisions that can disable the design decisions regarding disassembly. (Ciarimboli & Guy, 2005) Renting the building as service that is repaired and maintained by the supplier can also help the reusability of the materials. (Crowther, 1999) The factor regards participation of stakeholders and is therefore a process based factor. Involvement during the entire building development can lead to better choices during the use-phase.

2.7.2.4. Disassembler expertise

Disassembler expertise relates back to both the worker expertise (Ciarimboli & Guy, 2005; Soh et al., 2014) and the labor practice. (Ciarimboli & Guy, 2005; Crowther, 1999; Rios et al., 2015) More expertise with disassembly can lead to an easier disassembly process.

2.7.2.5. Number of operations

The number of operations required is not entirely a standalone factor. Every operation necessary to disassemble a component is the result of required tools, type of connection, accessibility of connection, etc. and more operations require more time (Peeters et al., 2012), resulting in more costs. As labor costs are one of the biggest contributing factor (Dantata, Touran, & Wang, 2005), reducing number of operations will increase economic incentive for disassembly. Because it reflects the complexity the disassembly process (Ciarimboli & Guy, 2005) it is considered as a process-based factor but closely related to design and financial-based factors.

2.7.2.6. Deconstruction safety

Deconstruction safety is part of the disassembly process at the end-of-lifecycle of a building. Which makes it a process-based factor. There is extensive regulation regarding building and demolishment safety plans. (Hoogervorst, 1999) When the safety cannot be guaranteed during the disassembly process, the operations cannot be performed. In bouwbesluit 2012 (Artikel 8.7 Veiligheidsplan, Bouwbesluit 2012) a guide for developing a construction and demolishment safety plan. Deconstruction operations fall in this category but it does not specifically mention deconstruction. The requirement of extensive environmental health and safety protections should be avoided. (Ciarimboli & Guy, 2005)

2.7.3. Financial based disassembly factors

The circular economy aims to capture value from circular feedback loops. (Ellen MacArthur Foundation, 2013) when economic incentive is not there, due to costs related to disassembly, this will not be chosen as option at the end of life phase of a building. Financial feasibility is directly related to the required time for disassembly and the costs. Other technological and process-based factors may decrease time and costs. Financial factors play a determinant role in the deconstruction phase.

Table 8: Financial-based factors for disassembly

Disassembly factor	Times mentioned in literature
Disassembly costs	4
Disassembly time	6

2.7.3.1. Disassembly time

Disassembly time and disassembly costs are closely related as labor costs are one of the biggest contributing factor for deconstruction. (Dantata et al., 2005; Vanegas et al., 2017), which is why it is considered a financial-based disassembly factor. The time required for disassembly may vary between three to eight times that of mechanical demolition. When time is a critical factor, deconstruction may not be a feasible alternative to demolition. (Rios et al., 2015). Many factors considered have an influence on the time required for disassembly. Disassembly time determines the length of the deconstruction phase.

2.7.3.2. Disassembly costs

Costs may be a hinderance to deconstruction. There is a common perception that cost pertaining to deconstruction is greater than demolition and disposal. However, studies had shown that it is not always true. (Rios et al., 2015) A reduction in disassembly time and costs can increase the viability of the circular economy (Vanegas et al., 2017). Residual value of materials can help in decreasing the costs compared to demolishment. “Upfront, operating and back-end” costs in providing the services of the built environment should be considered in the initial building design which can change the financial model and increase financial feasibility of disassembly. (Ciarimboli & Guy, 2005)

2.8. Discussion

This literature research consists of two parts. First of all the role of disassembly in the circular economy is considered. The CE principle consists of the biological cycle, economy model and the technological cycle. Disassembly enables material reutilization, which means that disassembly has an influence on the technical cycle. Disassembly is related back to three principles of the circular economy.

- Design out of waste
- Build resilience through diversity
- Think in ‘systems’

The Building Circularity Indicator assessment model is developed to determine the circular potential of a building. Disassembly determines fifty percent of the results of this model. Therefore it is important that these principles are incorporated correctly.

Disassembly has to be incorporated in the entire building development process and not only the design, a distinction can be made between technological, process and financial aspects in the circular economy. This can also be applied to building disassembly.

Material realization is enabled by disassembly but also by other factors. The circular economy model defines different material reutilization strategies. Building levels have an influence of how these strategies can be adopted. Other factors that determine the reusability of products are out of the scope of this research.

Limitations are identified in the BCI to assess building disassembly. These have to be solved to make the assessment represent the circular potential more accurately. A basis for solving the limitations is set in this chapter. The conceptual model and the proposed solutions to solve these limitations will be discussed in chapter 4.

Twenty-five factors that influence disassembly are identified from existing research. These are categorized as technical, process-based and financial-based factors which serves to implement them in the BCI assessment model. Factors are considered independently from each other, however dependencies are mentioned in existing research. Further research will be required to define the relationships between these factors. Implementing all disassembly factors in the BCI assessment model will make it too complex, therefore a selection has to be made.

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3

Determining the disassembly factors and their weights

The previous chapter describes the Building Circularity Indicator assessment model and some limitations of the assessment of disassembly in the model. Then twenty-five factors that influence the disassemble potential of a building are identified from existing literature. A differentiation is made between technical, process-based and financial-based factors which can be used to determine how they are incorporated in the BCI assessment model. The building development process is divided in different phases. Disassembly should be considered integrally throughout this process. Therefore the surveys should target respondents from these phases.

Adding all twenty-five identified disassembly factors to the BCI assessment model will make it comprehensive, but also more complex. Therefore the decision is made to implement the most important factors in the model. Furthermore, a hypothesis is made that not all disassembly factors weigh the same.

The Fuzzy Delphi Method is used to test this in two survey rounds. The first round serves to make a selection of most important disassembly factors to implement in the BCI assessment model and the second round serves to determine the weights of these factors. The results of the survey are displayed and discussed in this chapter.

3.1. Fuzzy Delphi Method

Durmisevic (2006) applied the Fuzzy set theory to measure the imprecise cases of the Disassembly Determining Factors. Almost every building is a prototype of itself because it is specifically designed and developed to the wishes of the client and to fit in the location of the building. This makes the way products are used in an assembly unique for a lot of situations. Measuring disassembly potential through experiments like in the industrial engineering (Vanegas et al., 2017) is impossible because of this.

Therefore is opted to conduct a survey to weight the impact of the disassembly factors on disassembly potential. Experts in the field of circular economy and disassembly during the entire building development process are asked to indicate how important they think the disassembly factors are to make this possible.

Applying the Fuzzy Delphi Method (FDM) to group decision could solve the fuzziness of common understanding of expert opinions. (Glumac, Han, Smeets, & Schaefer, 2011) which is why this method is chosen to use for the survey. By asking experts to judge the relative importance of the factors on a linguistic scale with a triangular function, the degree of uncertainty of the experts is captured.

Two surveys rounds are conducted. The first round serves to validate the identified factors in the previous chapter and to determine which factors will be used to assess the disassembly potential in the new BCI assessment model. Not all factors can be implemented in the BCI because this will make it too difficult to use. The results of the survey are compared with the literature and a sensitivity analysis to determine the most important factors. This will also validate whether the factors in the current BCI model (Verberne, 2016) are the most important and if other than design factors should be included.

The second survey round is done to determine the relative weights of the factors. A hyptohsis is made that not all factors are equally important and this impacts the calculation in the BCI assessment model. This is tested with a more elaborate linguistic scale because a majority of factors are fallen off with the first survey and this will shorten the required time of respondents to fill in the survey.

The Fuzzy Delphi method is derived from the Delphi Method and Fuzzy set theory (Glumac et al., 2011) and consists of four steps which are first explained in the first paragraph;

1. Validation of the factors for disassembly.
2. Collection of expert opinions.
3. Setting up the triangular fuzzy number.
4. Defuzzification of the results.

To assess the robustness of the results a sensitivity analysis is conducted. This is done by determining varying weight sets for the different expert groups and comparing what the influence is on the importance of the factors.

For survey I a screen evaluation index is determined to limit the amount of factors taken into consideration for the BCI assessment model. The factors above the screen evaluation index are used to conduct survey II.

The weights derived from the importance of the disassembly factors will be tested with the test case described in chapter 4.3. This validation is performed to make a decision for which weights will be implemented in the BCI assessment model.

3.1.1. Validation of the factors for disassembly

The identified factors from the literature research are verified in the first questionnaire. This verification is done to prevent the second questionnaire from becoming too extensive, thus preventing respondents from completing it. This follows a similar process to the second survey. Setting up the screen evaluation indexes is only used in the first survey to determine the definitive factors that are considered in the second survey.

3.1.2. Collection of expert opinions

In the previous chapter is stated that disassembly factors should be adopted integrally throughout the entire building development process. (Chapter 2.6.3) Therefore it is important to consider opinions of respondents in the different phases. None of the identified factors are assigned to the initiative phase, which is therefore combined with the design phase. To make sure everyone can fill in the survey, the student / teacher expert group is added. For the first survey the professional network of employees of Alba Concepts is consulted to create a list of experts to contact directly. The respondents in the first round were asked if they are willing to participate again in the second round. The second survey round requires a bigger response. Respondents are contacted directly and a social media post is promoted on LinkedIn to gather more expert opinions.

Table 9 shows an overview of the expert groups and examples of stakeholders considered to be part of these groups. The respondents are asked in each questionnaire in which phase they primarily work to assign their input to the corresponding expert group.

Table 9: An overview of expert groups and examples of stakeholders that are part of these groups.

Expert group	Group description	Examples of stakeholders
Preparation (includes initiative and design)	Respondents working in the early stages of a building development process where the concept is defined and the design is developed untill the project is awarded to a contractor.	Clients
		Architects
		Consultants
		Real estate developer
		Project developer
		Specialized engineers
		Etc.
Realisation	Respondents working in the realization stage of a building development process where the construction is prepared until the actual building is delivered to the client.	Contractor
		Specialized engineers
		Project managers
		Sub-contractors
		Supplyers
		Etc.
Exploitation*	Respondents working in the exploitation stage of a building	Future user
		Clients

	development process where the building is used until the building is prepared for removal.	Maintenance planner Maintenance contractor Etc.
Deconstruction	Respondents working in the deconstruction stage of a building development process where the building is to be removed until the materials which are released are reused or disposed of.	Demolishment contractor Material resellers Clients Hazardous material removers Supplyers Etc.
Student / teacher*	Respondents that are studying or working in the academic field of the built environment.	Student in the built environment Teacher in the built environment

For the first survey round the exploitation expert group is under represented and no respondents from the students/teachers expert group are targeted in this round. For the second survey round the exploitation expert group and the student/teacher expert group are both under represented. Therefore these expert groups are discarded in this research. This means that the opinion of these groups are not considered.

The first survey asked the respondents if in their opinion a factor is unimportant, sometimes important or always important to enable building disassembly. (Figure 14) Furthermore, the respondents were asked if any factors are missing. This is used to determine if the list of disassembly factors is complete.

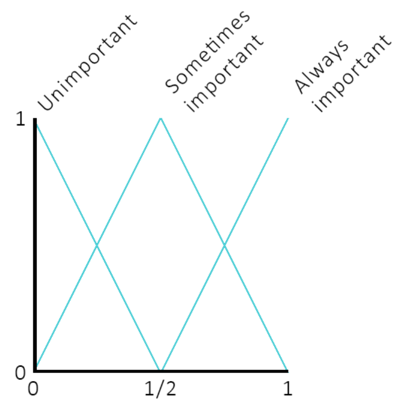

Figure 14: Linguistic scale of relative importance for the first survey

The second survey results in the relative weight of the disassembly factors. A more detailed nine-point scale is used in this survey. The respondents are asked to first select a lower-bound and an upper-bound in a bandwidth of which they think the importance is likely between; for example the importance varies between unimportant (lower-bound) and important (upper-bound). This is then complemented with a most common level of importance; for example neutral. These will make up a triangular fuzzy number. The bandwidth is defined from very unimportant to very important with levels in between to make up a nine-point scale. (Figure 15)

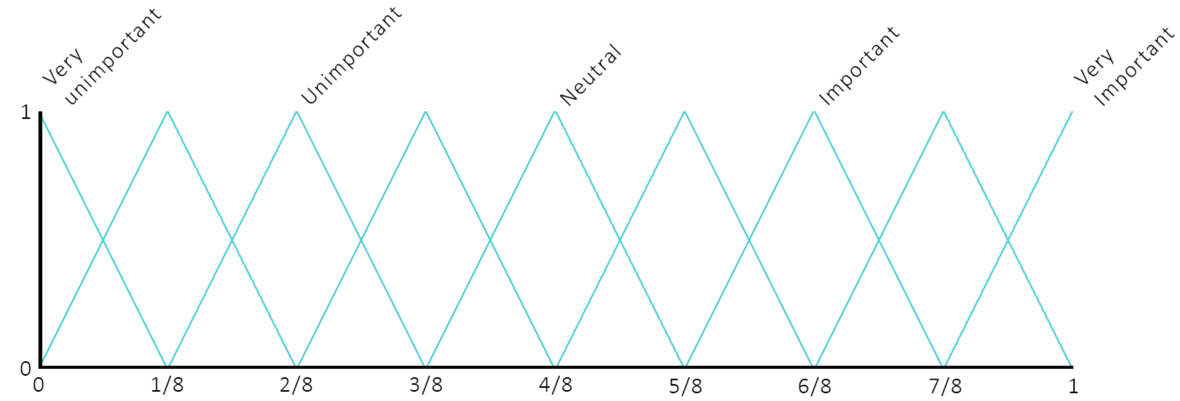

Figure 15: Linguistic scale of relative importance for the second survey

3.1.3. Setting up the triangular fuzzy number

For every factor j of m factors and every respondent i of n respondents the triangular fuzzy number is derived. The results are given in a matrix.

	C_1	C_2	…	C_m
R_1	$L_{1\,1}$		…	$L_{1\,m}$
R_2	$L_{2\,1}$	$L_{2\,2}$	…	$L_{2\,m}$
…	…	…	…	…
R_n	$L_{n\,1}$	$L_{n\,2}$	…	$L_{n\,m}$

In which
C_j = the j^{th} factor, $j = 1, 2, \dots, m$
R_i = the i^{th}expert respondent, $i = 1, 2, \dots, n$
L_{ij} = the linguistic value of factor j by expert i

For every factor j for every respondent i the triangular fuzzy number is calculated with the equation $\tilde{\omega}_{ij} = a_{ij} + b_{ij} + c_{ij}$. This is done by using the lower-bound score a_{ij} and the upper-bound score c_{ij} of the bandwidth and the optimal score b_{ij} as explained before. This is important because this will help understand the fuzziness nature of the response. The issue with measuring disassembly is that traditional models based on correlation co-efficiency have a high level of imprecision when dealing with linguistic data. (Durmisevic, 2006) The following formulas is used to determine the triangular fuzzy number. The general mean model is used to determine the overall mean number of factor j. (Klir & Yuan, 1995).

$$\tilde{\omega}_j = a_j + b_j + c_j$$

In which;

$a_j = \min\{a_{ij}\}$
$b_j = \frac{1}{n}\sum_{i=1}^{n} b_{ij}$

$c_j = \max\{c_{ij}\}$

This is done for both the first and the second survey. While the first survey only asks for one option instead of a bandwidth, the minimum and the maximum of their options are used for the bandwidth a_j and c_j.

3.1.4. Defuzzification

The center of gravity method is used to determine a singular number for every aspect $\tilde{\omega}_j$ (Klir & Yuan, 1995). This is done by using the following equation.

$$S_j = \frac{a_j + b_j + c_j}{3}$$

This is done for every factor and with this the relative weight is determined. For the first survey the result will differ much less because the answers are very close to each other. This is sufficient because only the most important factors are interesting in this research. The second survey is used to determine the relative weights and because the respondents are asked to fill in multiple scores (bandwidth plus optimal score) the likelihood of difference is bigger.

3.1.5. Sensitivity analysis

The goal of the sensitivity analysis is to test the robustness of the results. By assigning different weights to the results of the three expert groups, the data is transformed. The results are robust when there are little to no differences between them. To define different weights, power/interest matrices are composed for three theoretical scenarios. The results where all expert groups have an equal weight is also added to the sensitivity analysis.

By shifting power/interest on enabling disassembly in a building development process between expert groups, the importance of the results of an expert group increases or decreases.

The following assumption are used to determine the power/interest

- The power/interest is based on a three point scale for which 3 represents the most power/interest and 1 represents the least power/interests.
- The scale is regarded ordinal and therefore each score is used once.
- The power / interests of each expert group is multiplied with each other to determine how important the opinion of an expert group is.
- Weights are derived by normalizing for total importance of all expert groups.

In the first scenario the preparation expert group has a high (3) power to enable disassembly and a medium (2) interest. Subsequently the realization expert group has a medium (2) power and low(1) interests and the deconstruction expert group has a low (1) power and a high interest (3).

Table 10: Weights of scenario 1 for the sensitivity analysis

Scenario 1	Power	Interest	Importance	Weight
Preparation expert group	3,00	2,00	6,00	0,55
Realization expert group	2,00	1,00	2,00	0,18
Deconstruction expert group	1,00	3,00	3,00	0,27
Total			**11,00**	**1,00**

The second scenario is determined by increasing the importance of the realization expert group. This is done by shifting interest in enabling disassembly in a building development process from the deconstruction expert group to the realization expert group. The rest remains the same as scenario one.

Table 11: Weights of scenario 2 for the sensitivity analysis

Scenario 1	Power	Interest	Importance	Weight
Preparation expert group	3,00	2,00	6,00	0,46
Realization expert group	2,00	3,00	6,00	0,46
Deconstruction expert group	1,00	1,00	1,00	0,08
Total			**13,00**	**1,00**

The third scenario is determined by increasing the importance of the deconstruction expert group. This is done by shifting power in enabling disassembly in a building development process from the preparation expert group to the deconstruction expert group. The rest remains the same as scenario one.

Table 12: Weights of scenario 3 for the sensitivity analysis

Scenario 3	Power	Interest	Importance	Weight
Preparation expert group	1,00	2,00	2,00	0,15
Realization expert group	2,00	1,00	2,00	0,15
Deconstruction expert group	3,00	3,00	9,00	0,69
Total			**13,00**	**1,00**

3.1.6. Screen evaluation index

The screen evaluation index is used to determine which factors are considered in the second survey. Because building disassembly is influenced by many factors, it is important to limit the amount of factors that are taken into consideration to keep the model evident. Only the most important factors are implemented This keeps the BCI usable and still enables it to capture disassembly in an optimal way. Including all variables would also make the second survey too long which deters respondents from filling in the survey.

The screen evaluation index represents a threshold for α. When factors fall below the threshold in the first survey, they are disregarded for the second survey. This does not prove that they are irrelevant for building disassembly but a selection has to be made to implement factors in the BCI assessment model.

If $S_j \geq \alpha$, then factor j is considered important for the second survey.
If $S_j \leq \alpha$, then factor j is considered not important for the second survey.

3.2. Results survey I – Selecting the disassembly factors

This part explains the results to determine which disassembly factor are included in the BCI. The survey was sent out on the 5th of June 2018 and was open for respondents for three weeks. Respondents were directly contacted and no other media was used to distribute the survey. Because the target audience is Dutch speaking the survey is also designed in Dutch. Some factor names are slightly altered to represent the actual definition of the factor. A more elaborate definition is also given in the survey. The survey was designed in Google Forms and is included in Appendix 2. The three-point linguistic scale shown in Figure 14 is used to answer the questions.

3.2.1. Respondents survey I

The first step is to validate the factors identified to be important for disassembly. A smaller sample size is enough to assess the importance of the factors. The target audience are various experts in the fields of circular economy, sustainability or disassembly in the built environment. The potential respondents are employees and relations of Alba Concepts. A total of 63 e-mails were sent out and a total of 32 have responded, making the response rate almost 51%. The respondents were first asked to specify in which phase of a building development they are working in. The respondents also had the option to fill in their own input regarding their expertise. This is enabled to get a better understanding of the various fields that the respondents acknowledge. Based on the examples of stakeholders shown in Table 9 these respondents are categorized accordingly to the respective expert groups.

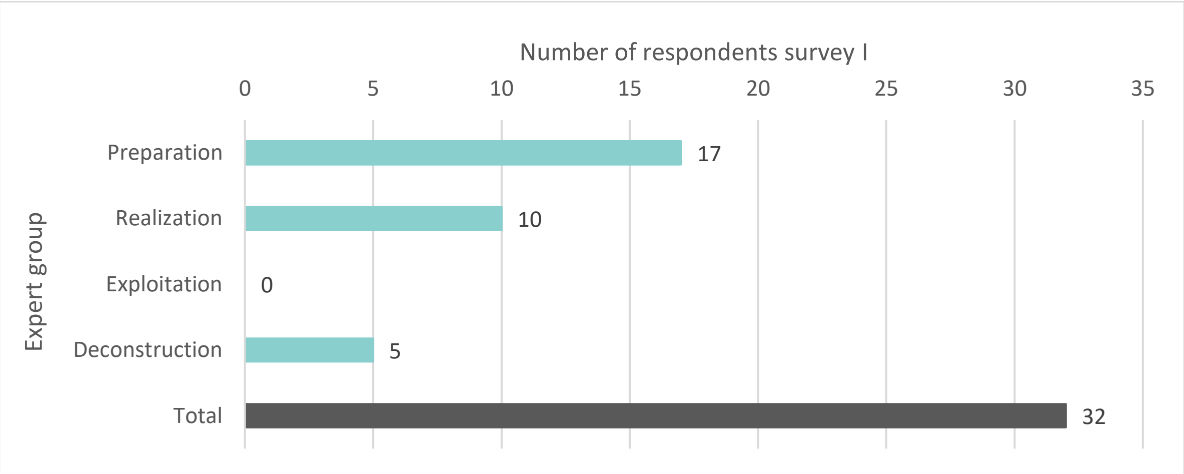

Figure 16: Number of respondents survey I

The target number of respondents per phase is between five and ten. There are seventeen respondents from the preparation expert group, ten from the realization expert group, zero from the exploitation expert group and five from the deconstruction expert group. The preparation expert group is overrepresented while the exploitation expert group is underrepresented. Because there are no respondents from the exploitation phase, this group is discarded which means that no opinions of experts from this phase are included in this research.

3.2.2. Importance of disassembly factors survey I

The results for survey I are displayed in Figure 18 and 21. This shows the unweighted importance separated by expert groups and the total importance considering all expert groups. There are some clear differences in importance between the expert groups and between disassembly factors. To check whether factors can be grouped together a Principle Component Analysis (PCA) is attempted. The PCA is a method to reduce variables by capturing most of the variances of the original factors in principle components. The PCA requires sampling adequacy to be applicable which is tested with the Kaiser-Meyer-Olkin test (KMO-test). (Laerd Statistics, 2018) The results of the KMO-test is unacceptable (between 0 and 49) and therefore the PCA is not applicable to the dataset. (Cerny & Kaiser, 1977) This means that no factors are grouped together and the current factors are preserved. A sensitivity analysis is performed to test the robustness of the results and to find out if this eliminates major differences between results.

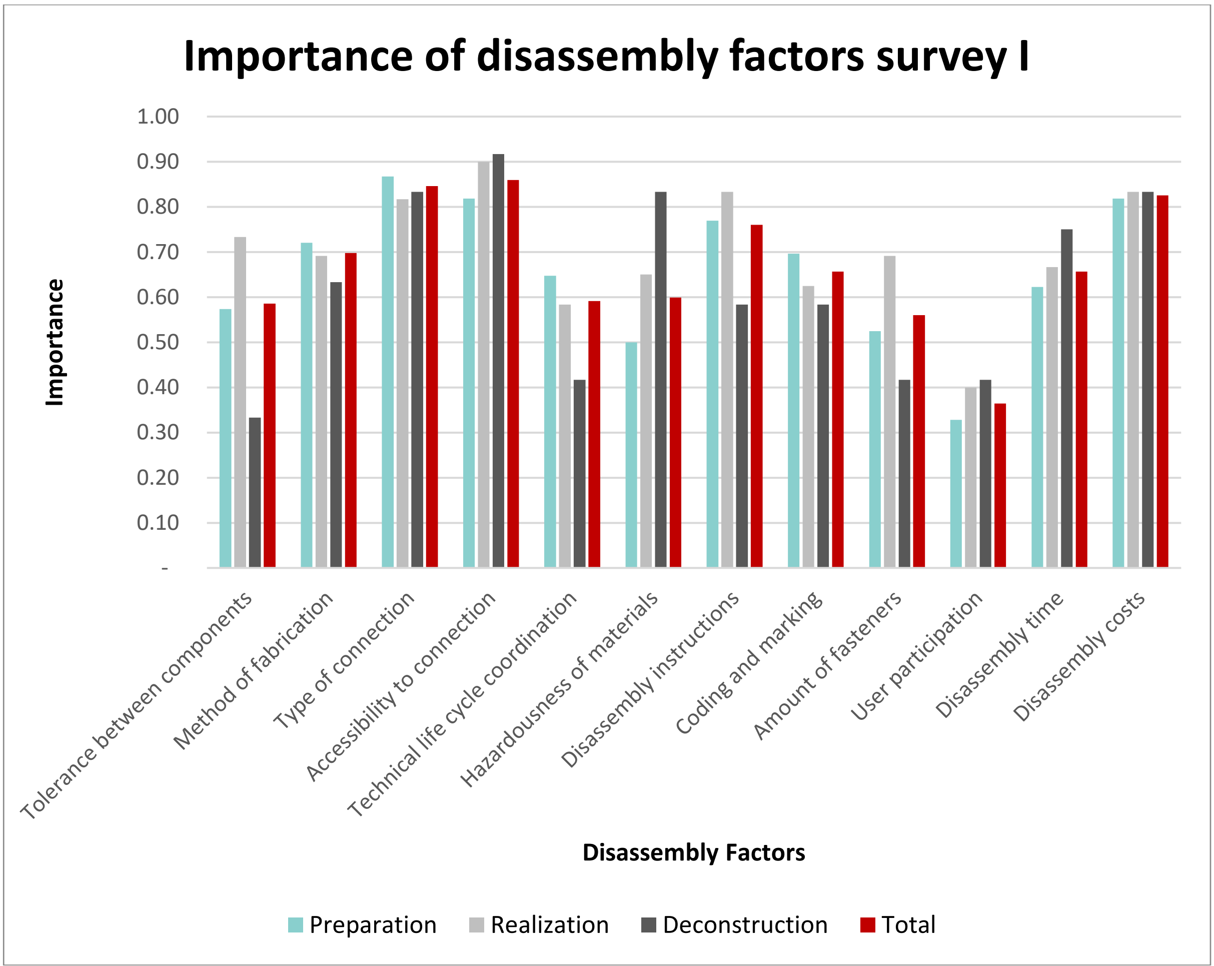

Figure 17: Importance of disassembly factors from survey I

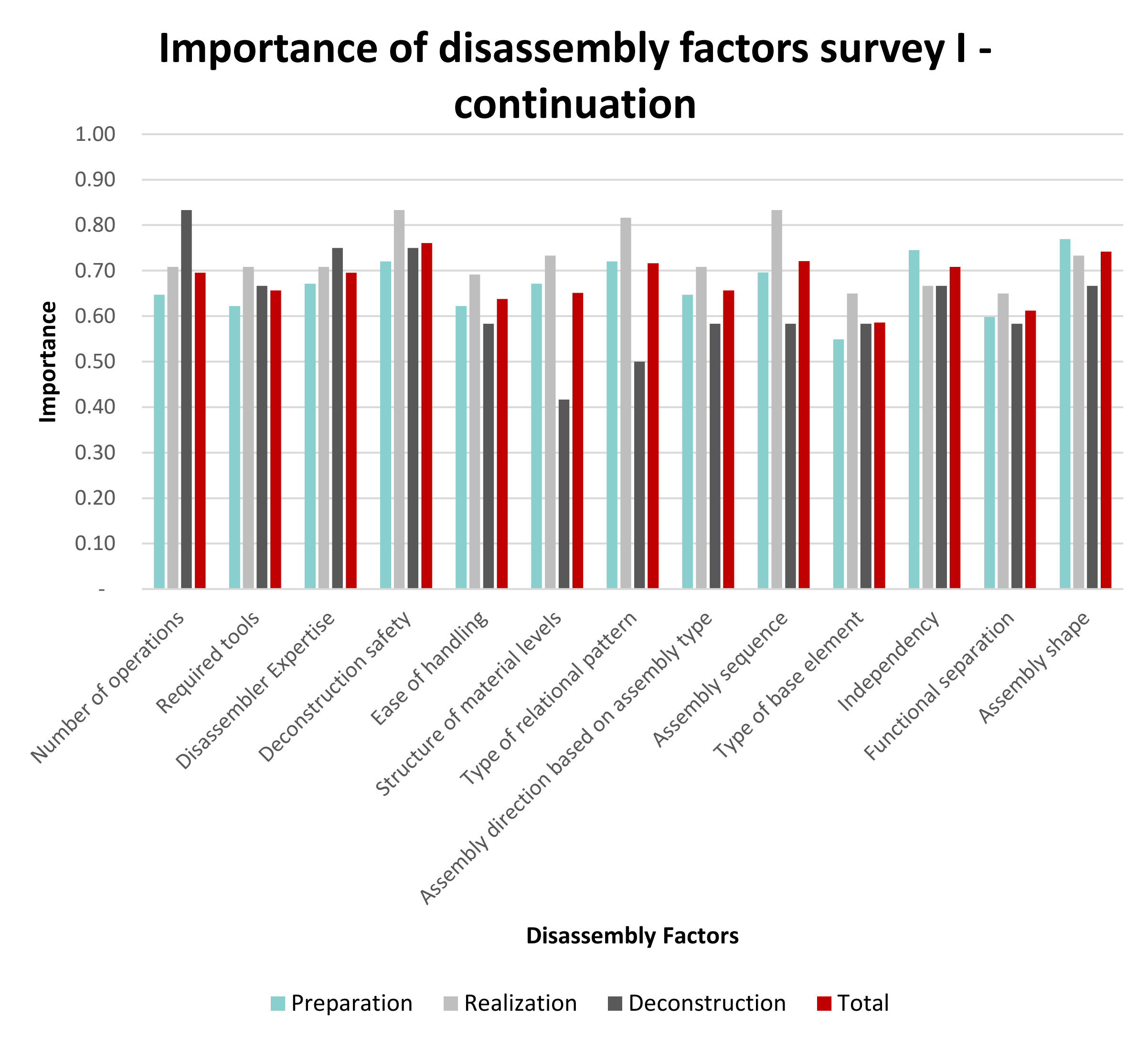

Figure 18: Importance of disassembly factors from survey I - continuation

3.2.3. Sensitivity Analysis survey I

A sensitivity analysis is conducted to assess the robustness of the results. This is done by comparing scenarios with different weights (determined in chapter 3.1.5) with each other. The results indicated with equal represent the total results from the previous paragraph. This means that all results for all expert groups are equally weighted.

Table 13: Scenario weights for different expert groups

	Weights			
Expert groups	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Equal**
Preparation expert group	0,55	0,46	0,15	1.00
Realization expert group	0,18	0,46	0,15	1.00
Deconstruction expert group	0,27	0,08	0,69	1.00

The result of the sensitivity analysis is shown in Figure 20 and 23. There are still minor differences in importance between the scenarios but the data can be considered robust. The outliers are mainly for the third scenario. Because the sensitivity analysis resolves the differences in results between the expert groups, the weighted importance is used to determine which disassembly factors are considered in the BCI assessment model.

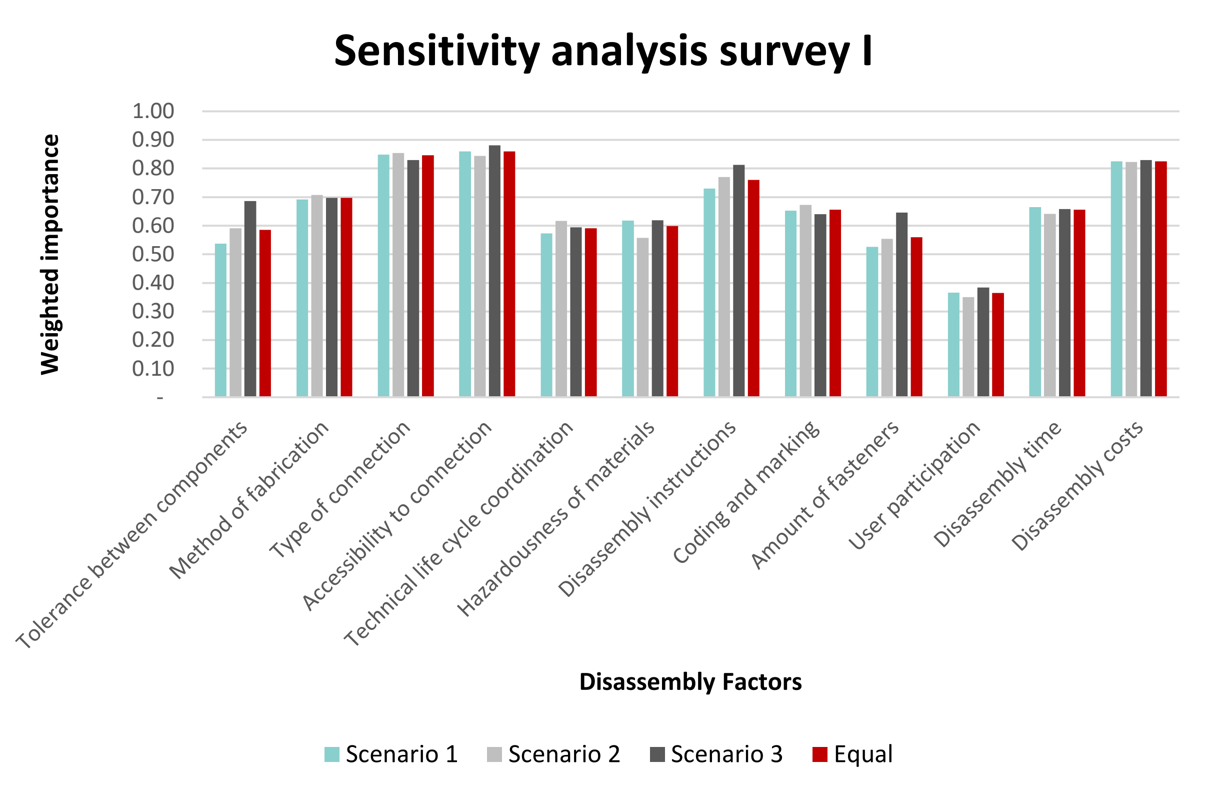

Figure 19: Sensitivity Analysis survey I using different weight sets

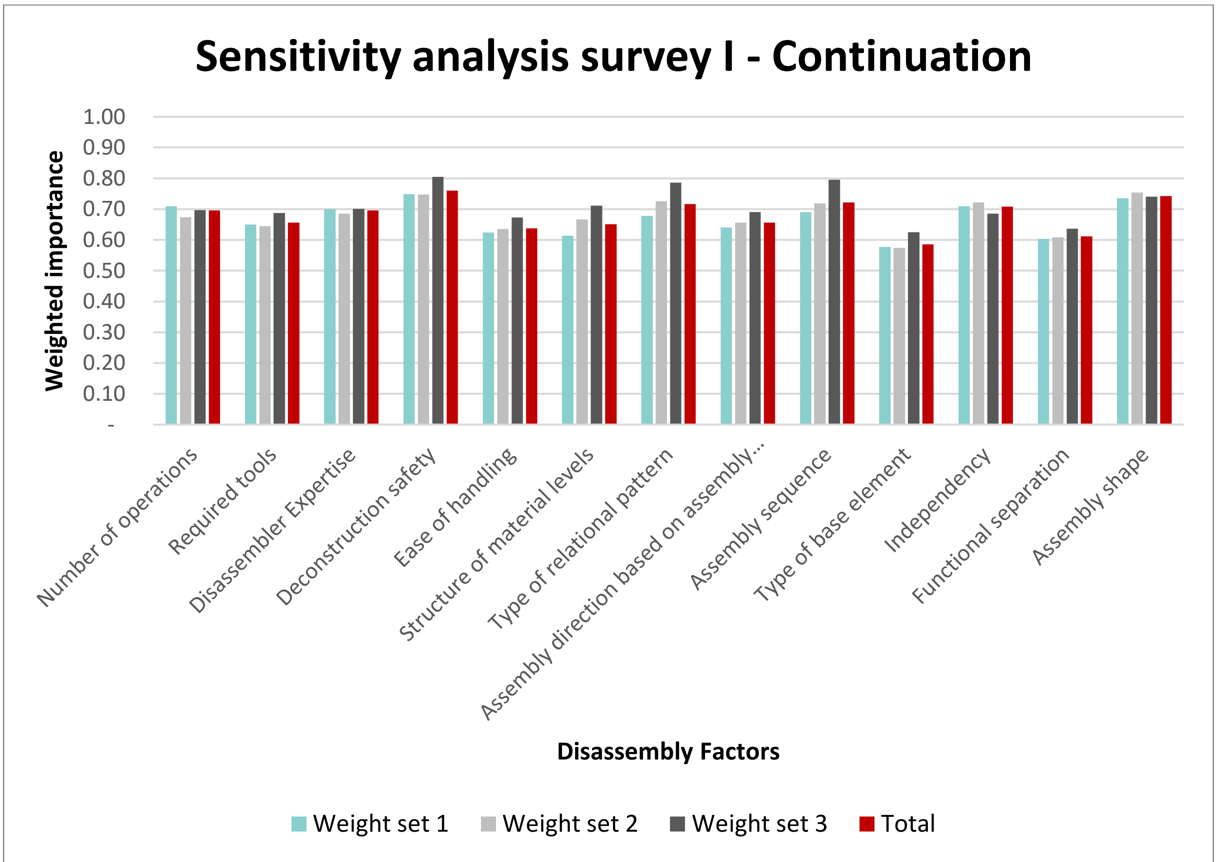

Figure 20: Sensitivity Analysis survey I using different weight sets - continuation

3.2.4. Determining the factors to include in the BCI assessment model

The decision is made to limit the amount of disassembly factors to incorporate in the BCI assessment model to twelve. This will increase the amount of factors included in the model from seven to twelve and this will ensure that the second survey round will not take too long to complete. Therefore the Screen Evaluation Index α is set to 0.68. Figure 21 and 25 show the weighted importance compared to the screen evaluation index. The results are sorted from high to low base on scenario 1.

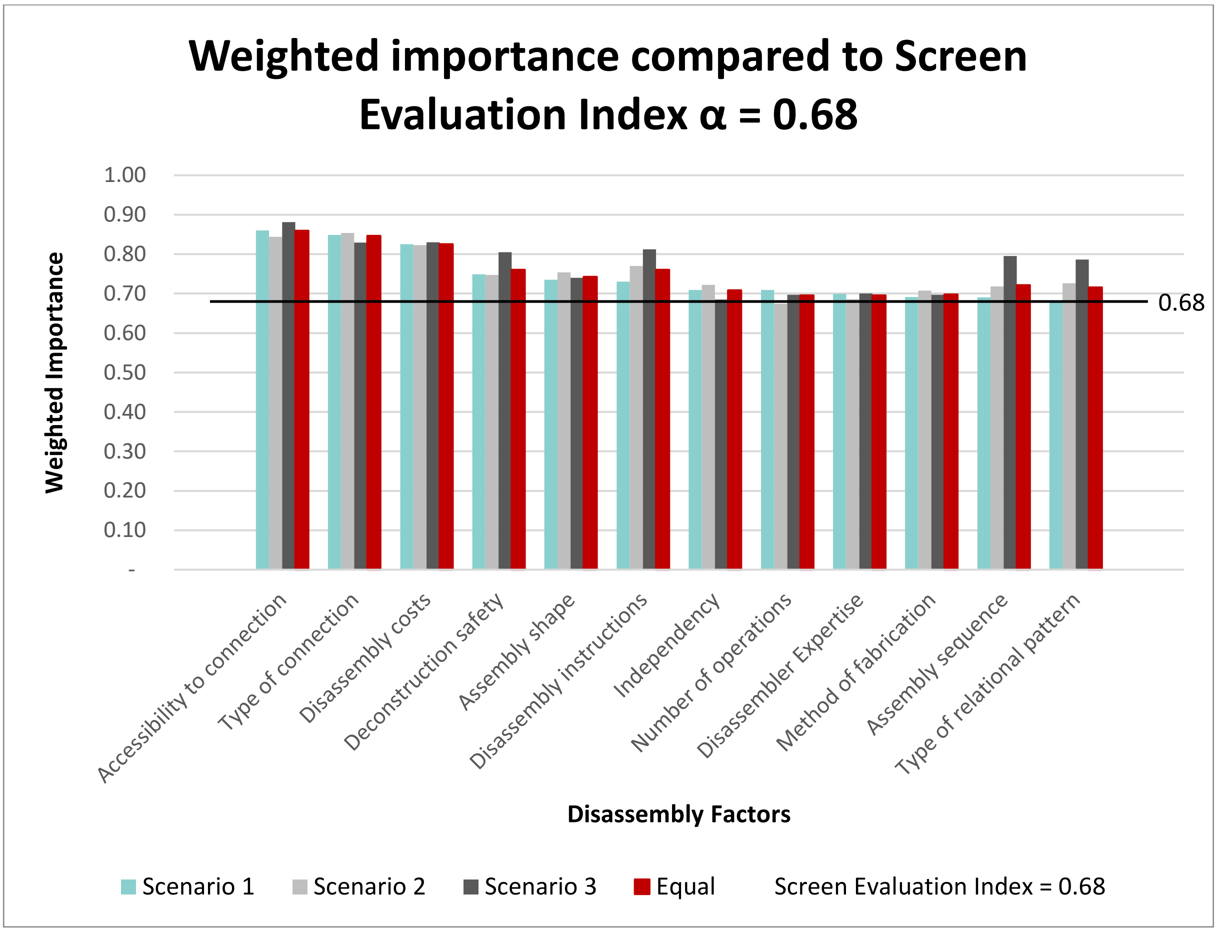

Figure 21: Weighted importance compared to Screen Evaluation Index α = 0.68

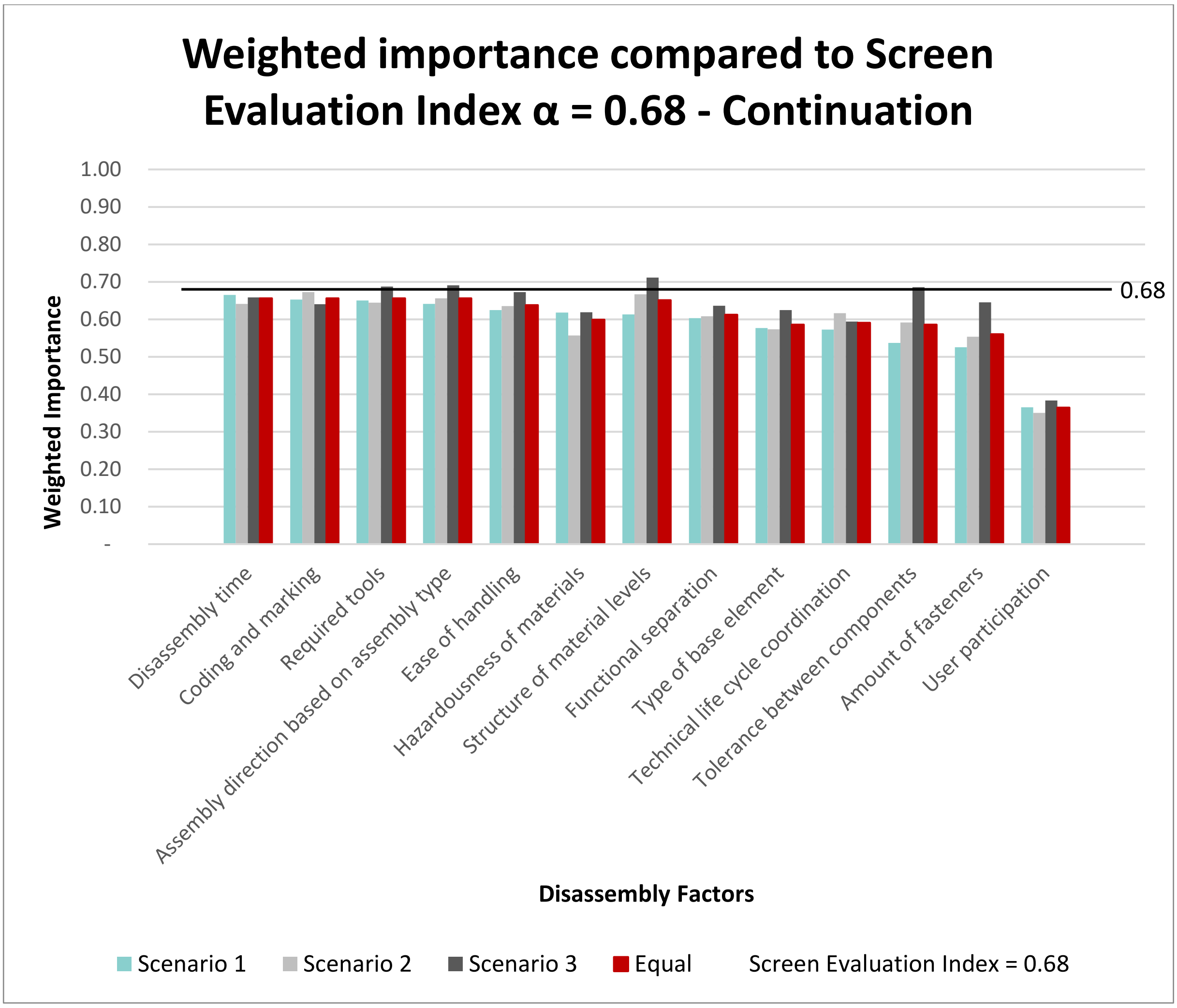

Figure 22: Weighted results compared to Screen Evaluation Index α = 0.68 - Continuation

A comparison is made between the twelve disassembly factors with a weighted importance higher than the screen evaluation index ≥ 0.68 and the literature research. The goal is to expand the amount of disassembly factors considered in the BCI assessment model, to implement a comprehensive set of factors regarding the IPF-model (van Oppen, 2017) (chapter 2.6.3) and to maintain the representation of the main categories of Disassembly Determining Factors (Durmisevic, 2006) (chapter 2.6.5)

Disassembly Factor	**Weighted importance ≥ 0.68 for all scenarios**	**Incorporate in the BCI assessment model (Verberne, 2016)**	**Type of factor**	**Type of DDF (Durmisevic, 2006)**
Accessibility to connection	🟢	🟢	Technical	Physical decomposition
Type of connection	🟢	🟢	Technical	Physical decomposition
Disassembly costs	🟢	🔴	Financial-based	
Deconstruction safety	🟢	🔴	Process-based	
Assembly shape	🟢	🟢	Technical	Physical decomposition
Disassembly instructions	🟢	🔴	Process-based	
Independency	🟢	🟢	Technical	Functional decomposition
Number of operations	🟡	🔴	Process-based	
Disassembler expertise	🟢	🔴	Process-based	
Method of fabrication	🟢	🟢	Technical	Physical decomposition
Assembly sequence	🟢	🔴	Technical	Physical decomposition
Type of relational pattern	🟢	🔴	Technical	Technical decomposition

Number of operations only scored lower than the screen evaluation index in scenario 2, which was 0.67. Seven new disassembly factors are added to the new BCI assessment model. This means two of the current BCI disassembly factors (Verberne, 2016) are discarded, namely;

- Functional separation and;
- Technical life cycle coordination

All aspects of the IPF-model are represented and all DDF categories are represented. Therefore these twelve factors are included in the new BCI assessment model.

The next survey uses a more elaborate linguistic scale which is conducted to determine the definitive importance of the twelve incorporated disassembly factors. Based on these results the disassembly factor weights are determined to incorporate in the BCI assessment model.

3.3. Results survey II – weighting the disassembly factors

The second survey is a continuation on the results of the previous survey. Twelve factors for disassembly are identified as most important and this survey round is designed to determine the weights of these factors to implement in the BCI assessment model. The survey is aimed at a broader target audience than the first survey. It was sent out on the 31st of July and was open for three weeks. The survey was sent out directly to respondents that submitted their e-mail address in the first survey and it was shared on Linkedin by myself and Alba Concepts various times. To reach enough respondents from the deconstruction expert group, the survey was shared by VERAS, the branch organization for demolishment companies, between their members. Because the target audience is entirely Dutch speaking, the survey is designed in the Dutch language. The survey is designed with the BERG Enquête Systeem 2.2. This is included in Appendix 3.

3.3.1. Respondents survey II

The survey has been accessed a total of 254 times and there were 91 respondents that filled in the survey entirely. This makes the response rate about 35.8% which is lower than the first survey. This was expected because this survey was focused on a broader public and there was less focus of directly contacting the respondents personally. For this survey the respondent groups were given as fixed choice. To make sure all respondents that opened the survey could fill in the survey, the exploitation expert group was preserved and the student/teacher expert group was added (Table 9).

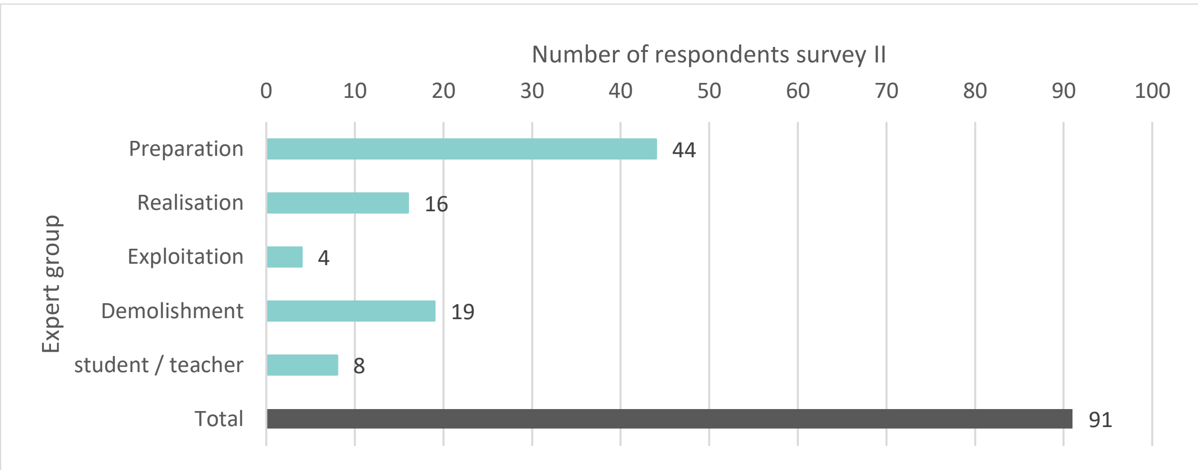

Figure 23: Number of respondents survey II

The target number of respondents per phase was between fifteen and twenty. The preparation phase, realization phase and demolishment phase are represented by sufficient respondents to incorporate in the results. The exploitation phase and the student/teacher respondent group are underrepresented which leads to the exclusion of these groups from the results. This makes a total of 79 respondents (about 87% of all respondents who filled in the survey) whose input is included in the results.

3.3.2. Importance of disassembly factors survey II

The importance of the disassembly factors are derived with the same method as used in survey I but with a nine-point linguistic scale. (Figure 15) This opens up the possibilities for bigger differences between importance of disassembly factors. Figure 24 and 28 display the results of survey II. There are differences in importance of disassembly factors between the expert groups. All results range between 5.00 and 7.50, which is not very big and this does not suggest major differences between the importance of different factors. A sensitivity analysis is conducted again to test the robustness of results and to understand whether this eliminates the differences between expert groups.

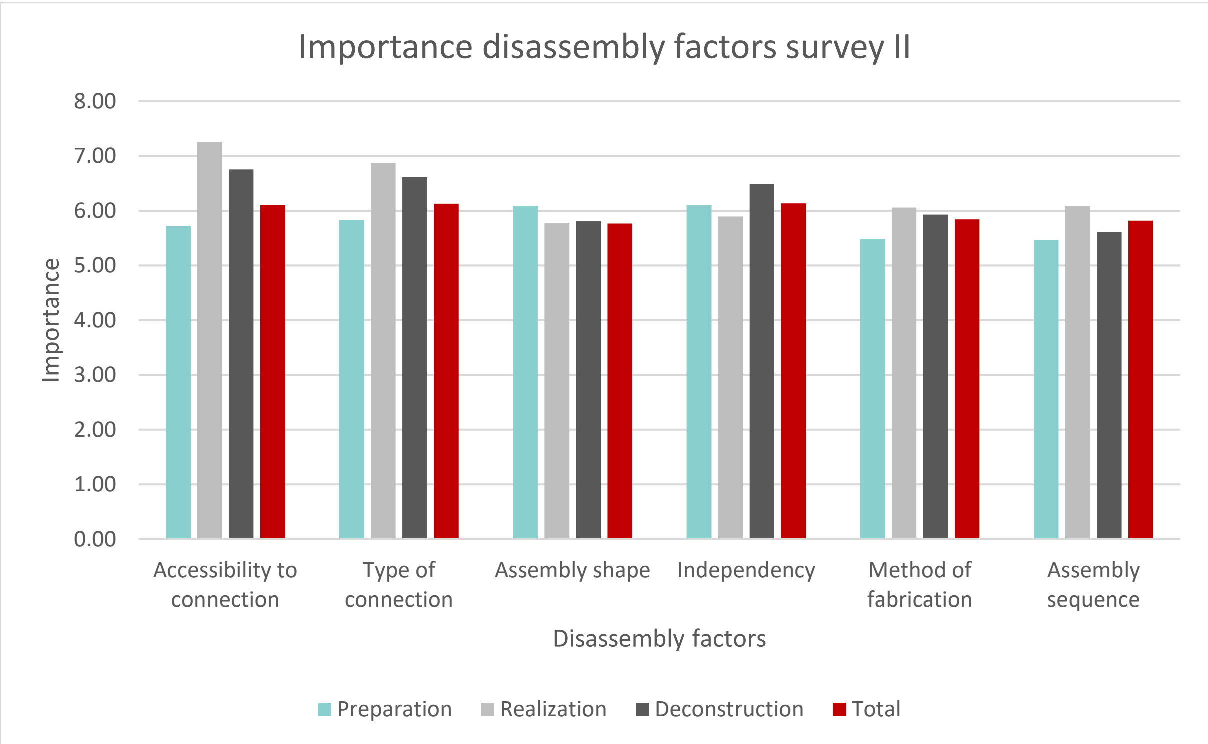

Figure 24: Importance of disassembly factors survey II

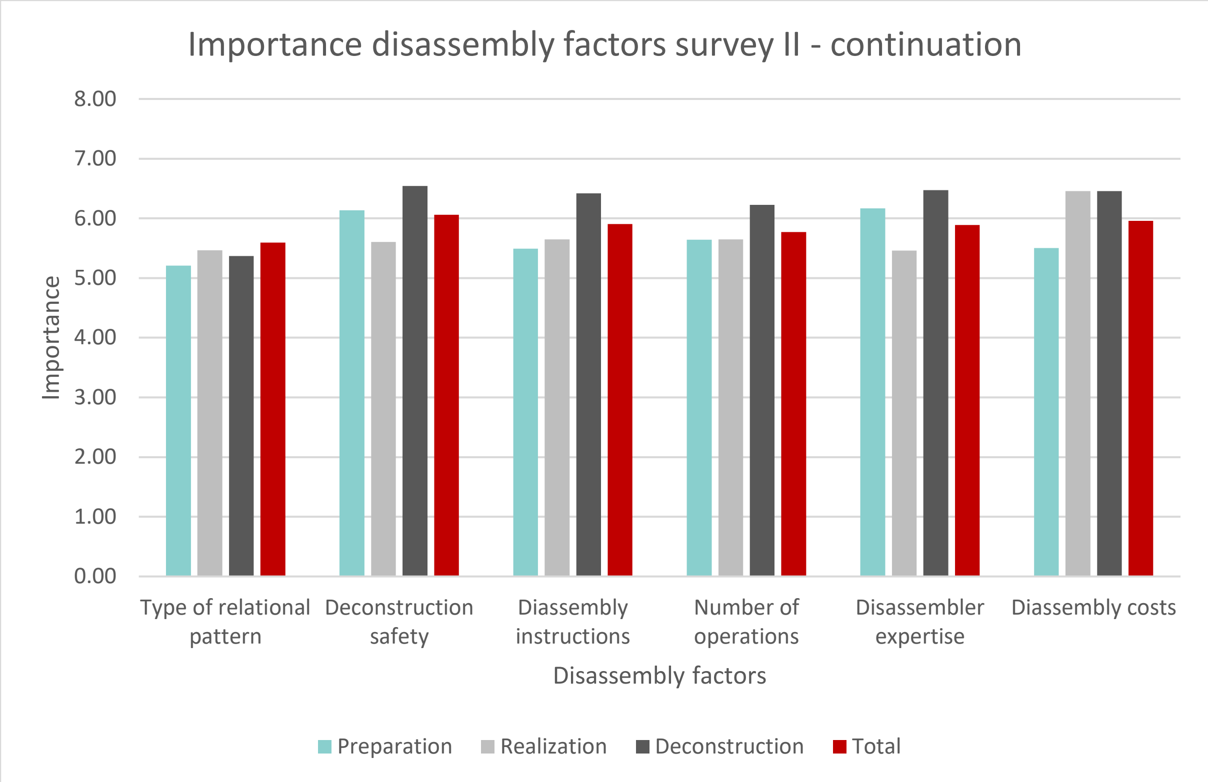

Figure 25: Importance of disassembly factors survey II - continuation

3.3.3. Sensitivity Analysis survey II

A sensitivity analysis is conducted to assess the robustness of the results. This is done by comparing scenarios with different weights (determined in chapter 3.1.5) with each other. The results indicated with equal represent the total results from the previous paragraph. This means that all results for all expert groups are equally weighted.

Table 14: Scenario weights for different expert groups

	Weights			
Expert groups	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Equal**
Preparation expert group	0,55	0,46	0,15	1.00
Realization expert group	0,18	0,46	0,15	1.00
Deconstruction expert group	0,27	0,08	0,69	1.00

The results for the sensitivity analysis are shown in Figure 26 and 30. The differences between scenarios are smaller than the unweighted results (chapter 3.3.2). The weighted importance still has a very low range. This will influence the impact of the weights in the BCI assessment model.

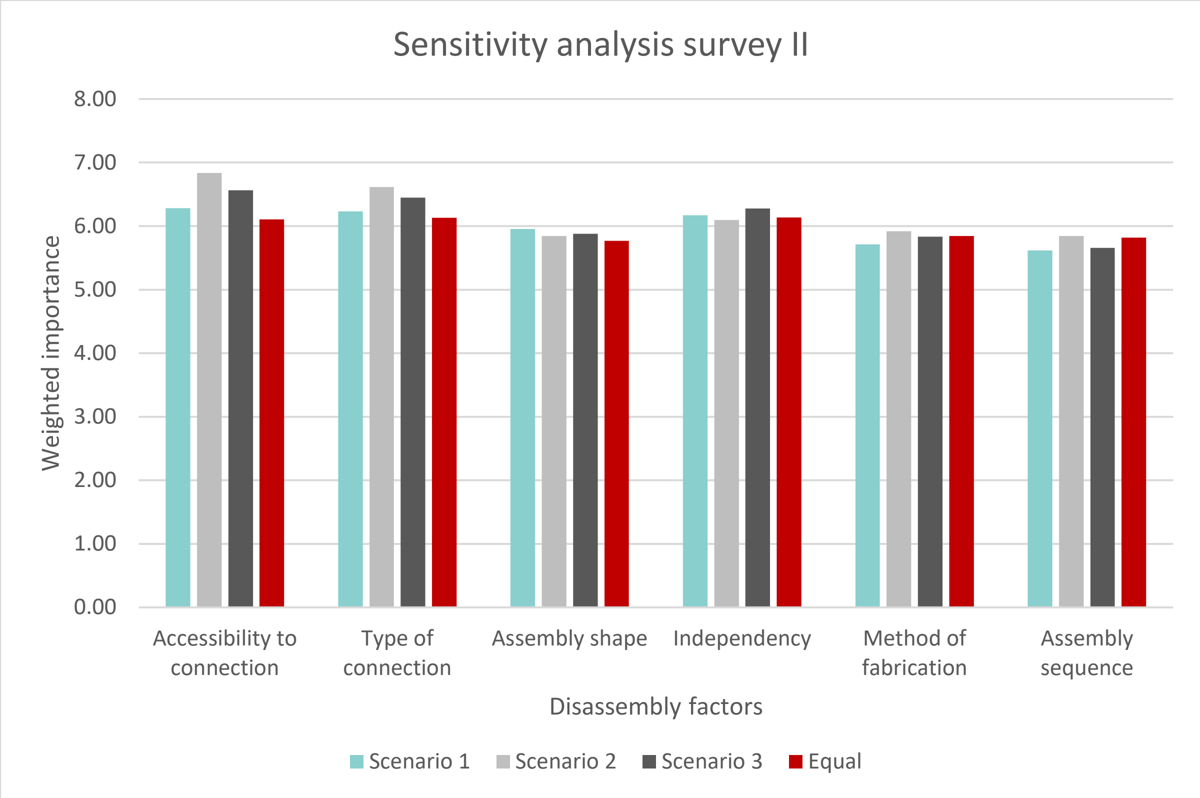

Figure 26: Sensitivity Analysis survey II using different weight sets

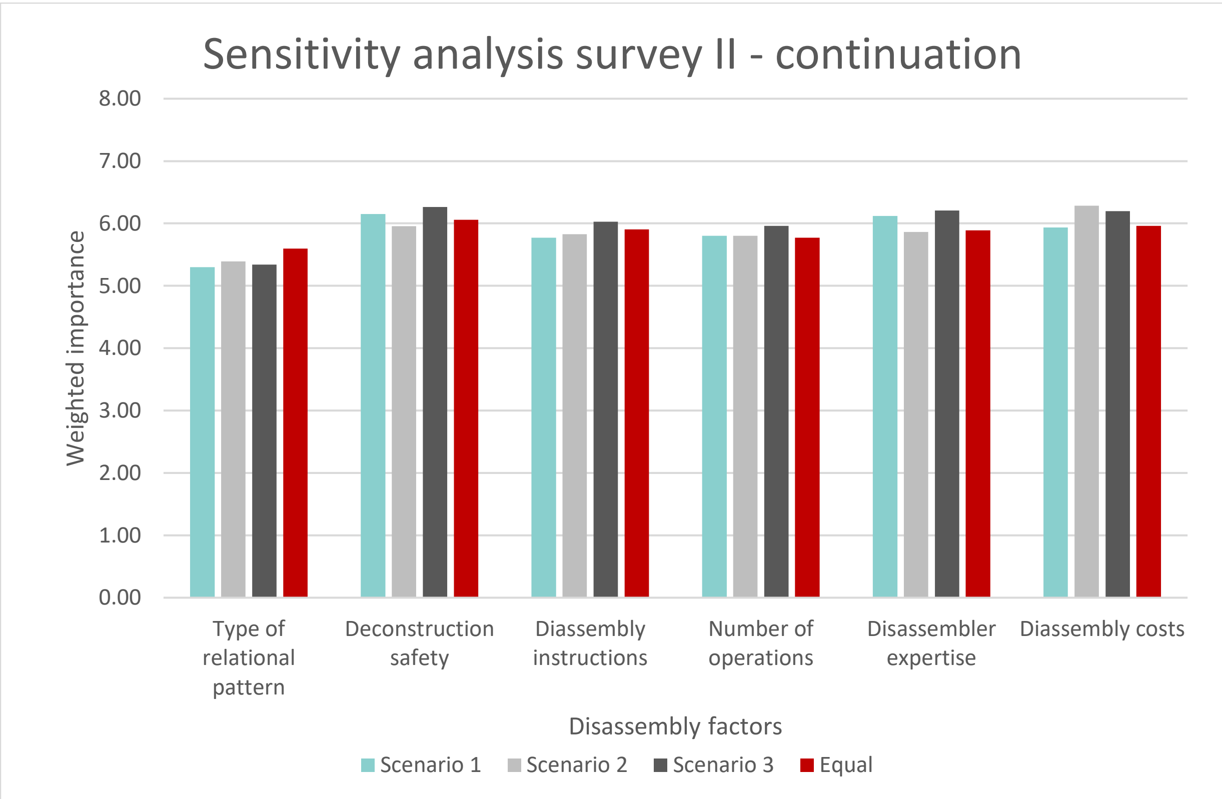

Figure 27: Sensitivity Analysis survey II using different weight sets - continuation

The hypothesis is that there is a difference between the weights of disassembly factors. However a visual inspection of the results already suggests little differences between the variables which does not support the hypothesis.

3.3.4. Determining the weights of disassembly factors

Based on the results the weights can be derived and the impact of the weights on the disassembly potential can be determined. This is used to decide which weights are incorporated in the model.

3.3.4.1. Difference between the disassembly factors

The second survey is conducted to determine the importance of the factors and use this to determine weights to implement in the BCI assessment model. Descriptive statistics show the mean, minimum, maximum, range, standard deviation and the variance for the disassembly factors in the different scenarios.

Table 15: Descriptive statistics for the importance of disassembly factors in different scenarios

	Importance			
Factor	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Equal**
Accessibility to connection	6.28	6.84	6.56	6.11
Type of connection	6.23	6.61	6.45	6.13
Assembly shape	5.96	5.84	5.88	5.77
Independency	6.17	6.10	6.28	6.14
Method of fabrication	5.71	5.92	5.83	5.84
Assembly sequence	5.62	5.84	5.66	5.82
Type of relational pattern	5.30	5.39	5.34	5.59
Deconstruction safety	6.15	5.96	6.26	6.06
Diassembly instructions	5.77	5.83	6.03	5.90
Number of operations	5.80	5.80	5.96	5.77
Disassembler expertise	6.12	5.86	6.21	5.89
Diassembly costs	5.93	6.28	6.20	5.96
Report				
Mean	5.92	6.02	6.06	5.92
N	12.00	12.00	12.00	12.00
Minimum	5.30	5.39	5.34	5.59
Maximum	6.28	6.84	6.56	6.14
Range	0.98	1.45	1.22	0.55
Std. Deviation	0.29	0.39	0.34	0.17
Variance	0.09	0.15	0.12	0.03

This table shows a very low standard deviation and variance between the factors for each scenario. This means that the importance of the different disassembly factors are very close to each other and indicates little differences. The expectation is that the different weights have no impact on the results for calculating the disassembly potential in the BCI assessment model. This is validated by testing the weights in the test case described in chapter 4.3.

3.3.4.2. Deriving weights for the BCI assessment model from the importance.

The importance of each factors is derived from a nine-point linguistic scale. To implement the weight of the disassembly factors and to validate them in the BCI assessment model, weights between 0 and 1 are required. By dividing the importance by 9 the weights for the disassembly factors are determined.

Table 16: Weights of the disassembly factors for different scenarios

	Weight			
Factor	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Equal**
Accessibility to connection	0.70	0.76	0.73	0.68
Type of connection	0.69	0.73	0.72	0.68
Assembly shape	0.66	0.65	0.65	0.64
Independency	0.69	0.68	0.70	0.68
Method of fabrication	0.63	0.66	0.65	0.65
Assembly sequence	0.62	0.65	0.63	0.65
Type of relational pattern	0.59	0.60	0.59	0.62
Deconstruction safety	0.68	0.66	0.70	0.67
Diassembly instructions	0.64	0.65	0.67	0.66
Number of operations	0.64	0.64	0.66	0.64
Disassembler expertise	0.68	0.65	0.69	0.65
Diassembly costs	0.66	0.70	0.69	0.66

3.3.4.3. Validating the weights of the disassembly factors

The weights determined in the previous paragraph are implemented in the new BCI assessment model and tested with the test case described in chapter 4.3. to assess the disassembly potential. The benchmark is set that every disassembly factors has the same weight, meaning ω_j= 1.00 for each factor j.

The results of implementing the different weights compared to the benchmark are shown in Table 17.

Table 17: Implementation of different weights for disassembly factors compared to the benchmark

		Product Disassembly Potential (PDp)			
Product	**Benchmark**	**Weight scenario 1**	**Weight scenario 2**	**Weight scenario 3**	**Equal**
BILT_wandpaneel	0.81	**0.80**	0.81	**0.80**	0.81
BILT_vloerpanel_BG	0.62	0.62	**0.63**	**0.63**	**0.63**
BILT_vloerpanel_1e	0.70	0.70	**0.71**	**0.71**	**0.71**
BILT_vloerpanel_dak	0.84	**0.83**	0.84	**0.83**	0.84
BILT_Kozijnpaneel_1200mm	0.97	0.97	0.97	0.97	0.97
BILT_Schroefpaal	-	-	-	-	-
BILT_Binnenwand_1200mm	0.66	**0.64**	**0.64**	**0.64**	**0.65**
BILT_Binnendeur	0.93	0.93	0.93	0.93	0.93
BILT_Verhoogdvloersysteem300x300	0.98	**0.97**	**0.97**	**0.97**	**0.97**
BILT_Buitenwandbekleding	0.77	**0.76**	0.77	**0.76**	0.77

The results show that by implementing the derived weights from survey II results in almost no differences compared to the benchmark. The hypothesis that there is a difference between the importance of different disassembly factors is cannot be accepted and the weights of the benchmark (ω_j= 1.00 for each factor j) are implemented in the BCI assessment model.

3.4. Discussion

3.4.1. Survey I

For the first survey, only five of the twenty-five factors have an importance below 0.6 which are ‘Type of base element’, ‘Technical life cycle coordination’, ‘Tolerance between components’ ‘Amount of fasteners’ and ‘User participation’ for which the last had a significantly lower importance with 0.4. This excluded the factor “technical lifecycle coordination” from the current BCI assessment model. Furthermore “functional separation” was at the bottom of the factors scoring a 0.6. Which also showed that this was considered less important than the other factors and therefore this is the second factor disregarded from the current BCI assessment model.

A limitation of factors is necessary to make the second survey doable for the respondents and to keep the new model for assessing disassembly evident. Because the second survey added the requirement to indicate a bandwidth and replaced the three-point linguistic scale a nine-point scale, the survey becomes too long to include all the factors. First of all a test to do a Principal Component Analysis was done to find out whether there a common component between several factors. The test indicated that it was statistically impossible to group components. A threshold was set instead to limit the factors.

The threshold is based on comparing the results of the survey with de results from the literature study. This results in a threshold of 0.68. This limited the number to twelve factors to incorporate in the BCI Assessment model and to continue with in the second survey round. This means that thirteen of the twenty-five identified disassembly factors are dropped from the research, ten technical factors, 2 process-based factors and 1 financial based factor.

Of the seven technical factors included in the new BCI assessment model, five are already implemented. This does not change the factors a lot. However the contribution is that this research provided a validation of these factors which was not done yet. The process-based an financial-based factors included are new and will be used as preconditions and drivers for disassembly in the BCI assessment model.

3.4.2. Survey II

The second survey aimed for more respondents from all the expert groups. First of all it is notable that the importance of the disassembly factors do not differ much.

The unweighted results variations between the opinions of different expert groups. The differences between the unweighted importance of each factor is discussed in appendix
A sensitivity analysis is performed to analyze the influence of different power/interest levels on the results and to see if this decreases the differences. Assigning different power/interest levels brings the results between expert groups closer together which makes them more comparable.

The variance between the different weighted results are very low which means that there is not much difference between the factors and the mean of these factors. The weights of different scenarios are tested in the new BCI assessment model to see what the influence is.

Because the influence is insignificant, the hypothesis is not accepted based on the results of this survey.

Building to enable disassembly at the end of the lifecycle of a building has been tried various times in the past (Crowther, 1999; Durmisevic, 2006; SenterNovem, 2007) but it is not common practice yet. It may be difficult to reflect the disassembly factors back to the practical implications. This can create bias because the respondent understand the proposed factors are considered to be important, otherwise they would not have been presented to them, but the actual level of importance is too difficult to estimate. It is recommended to perform a follow-up research to validate the responses with experts from the different fields with qualitative research methods. It is possible to use the results of the BCI assessment model to make the impact of the factors more understandable during this validation process.

Because the factors that are dropped off were all considered influential for disassembly in the literature study, it is recommended that further research regarding the influence of these factors is done. All the factors are now considered as independent variables. In the literature some dependencies between factors are already stated. When considering how these factors influence each other, a better understanding can be gained of disassembly and what the loss of information is by disregarding these factors.

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4

Developing the BCI assessment model

In the previous chapter a selection of twelve out of twenty-five identified disassembly factors is made. The weights of these factors are tested and are found to be equally important. These disassembly factors will be incorporated in the BCI assessment model.

Based on the limitations of assessing building disassembly potential and the selection of disassembly factors a conceptual model is developed. This new conceptual model aims to solve these limitations by assessing disassembly potential integrally in the model. The steps for developing the new assessment model are described in this chapter.

By validating the new assessment model with a case study and by comparing the results with the old model, it is tested for face validity. The results of the case study are discussed in the final part of this chapter.

4.1. Conceptual model

The Building Circularity Indicator assessment model is a theoretical model developed to create a simple measure of achievement to enable the transition to a circular economy. (Verberne, 2016) The BCI focusses on the technical cycle in the circular economy model and defines eleven Key Performance Indicators. Four of these are included in the calculation model of which one is disassembly possibilities.

Essentially four steps are undertaken to calculate the BCI;

- Calculate the MCI with the material input, output and lifecycles of products
- Calculate the PCI by determining the disassembly possibilities of products and multiplying this with the MCI of the products
- Calculate the SCI by categorizing products according to shearing layers of Brand and normalizing with a factor like weight, volume, price, etc.
- Calculate the BCI by multiplying the SCI with the level of importance of the shearing layers of Brand.

The other KPI's are included as preconditions, which organizations can include in their procurement and drivers which reflect financial drivers to transition towards a circular economy.

The conceptual model of the BCI assessment model is displayed in Figure 28 which displays these steps and the extensive calculation method is added in Appendix 1.

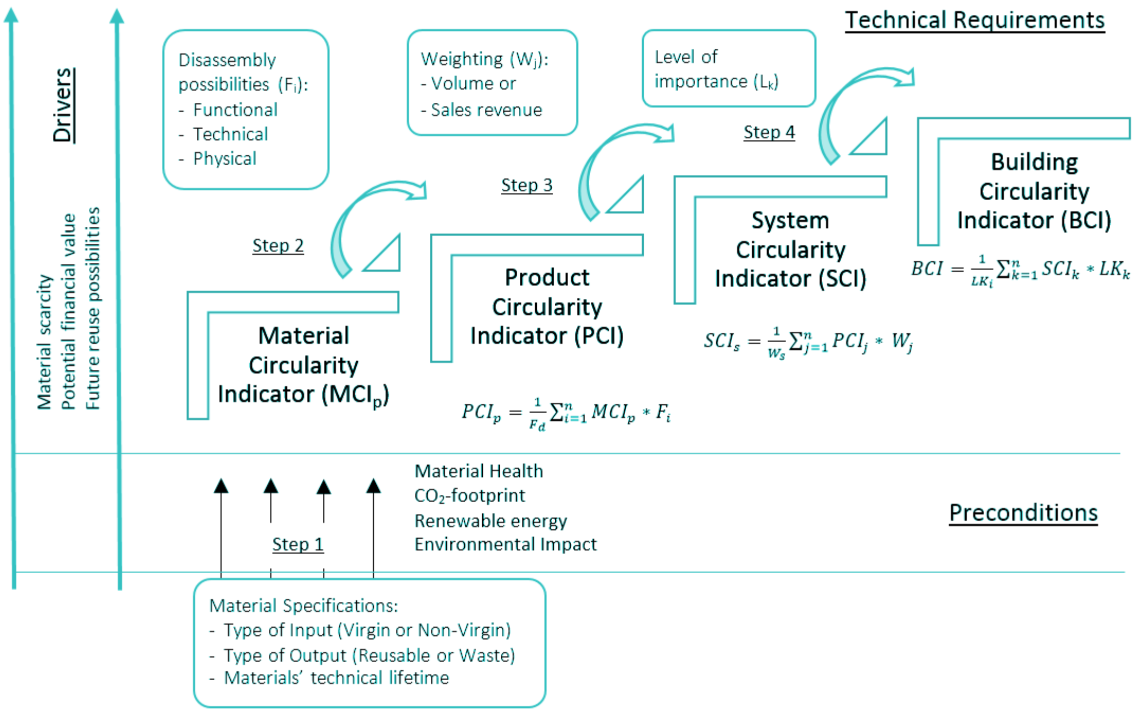


Figure 28: Conceptual model of the Building Cicularity Indicator assessment model (Verberne, 2016)

Essentially disassembly has a predominant role in calculating the BCI because it defines fifty percent of the result. This research identified some limitations in the BCI regarding calculating the disassembly possibilities. Before the BCI can be adopted by the industry as simple measure of achievement to drive the transition towards a circular economy (Kok et al., 2013), these limitations have to be solved. This research aims to do so by redeveloping the method for assessing disassembly in the BCI assessment model. The identified limitations are:

- A Bill of Materials (BOM) is developed of a building project to use as input to calculate the BCI. There is no industrial standard to develop a BOM. This leads to differences for which building levels are considered in a calculation and makes comparison of results between projects difficult.
- There is no framework to assess disassembly possibilities. This makes it very difficult to reason back which argumentations are used to assess the disassembly factors included in the model. Because disassembly factors are sensitive to subjectivity, hence the fuzzy variables, it is easy to create different assessment based on personal interests without framework
- No research is done if the disassembly factors incorporated in the BCI assessment model are comprehensive. Only functional, physical and technical factors are included in the BCI. Disassembly should be incorporated integrally in the building development process.
- All disassembly factors are equally important but the hypothesis is made that factors have different levels of importance (weights) in enabling disassembly.
- Disassembly is regarded once while calculating the PCI but the circular principles include thinking in 'systems', the ability to understand how parts influence one another within a whole, and the relationship of the whole to the parts is crucial. (Ellen MacArthur Foundation, 2013) Shearing layers of Brand define the SCI and separates these layers from each other. This neglects any relations between the systems.
- The goal of disassembly is to reuse building materials. Disassembly possibilities are assessed but no relation with reusability is made.

A new conceptual model is built to solve these limitations. This has an influence on the way the BCI assessment model is calculated. The proposed conceptual model for the new BCI assessment model is shown in Figure 29.

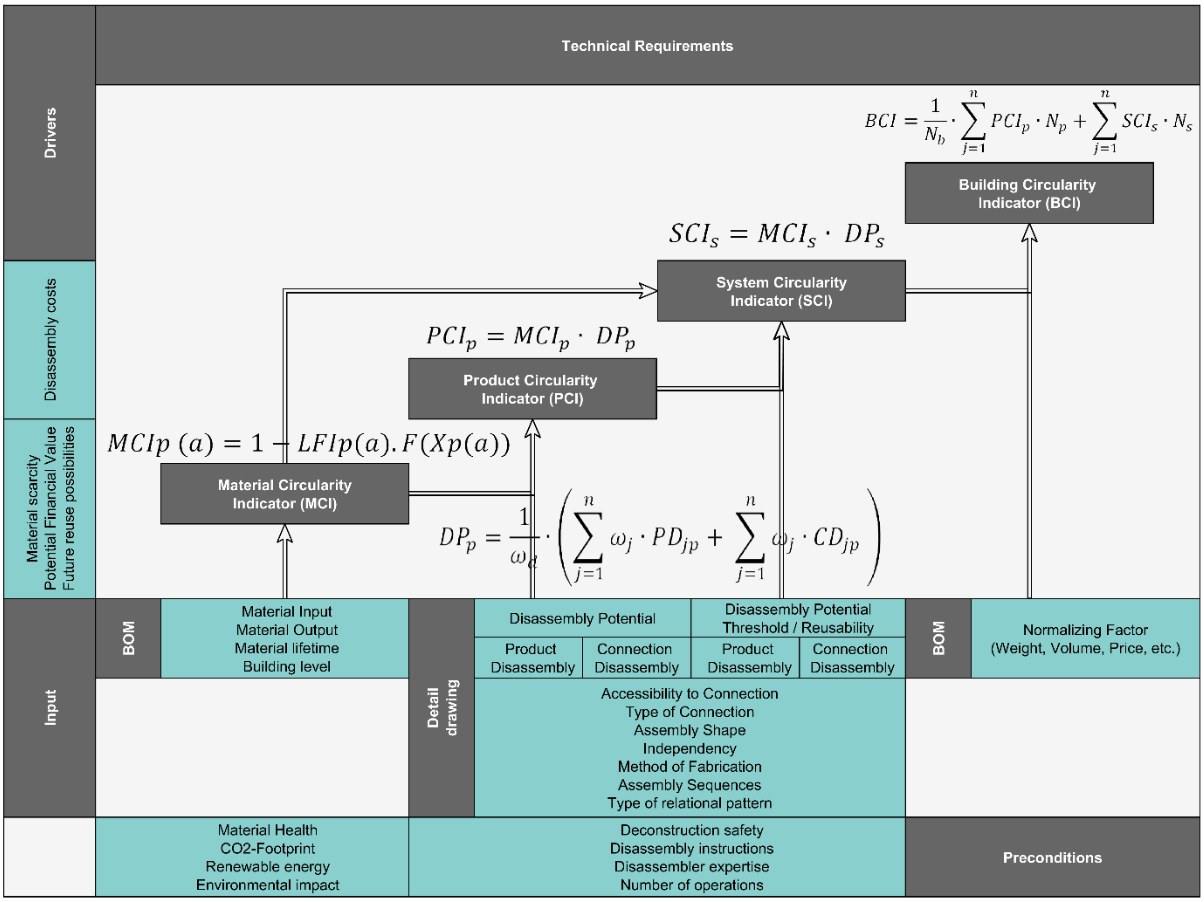


Figure 29: Conceptual model for the new Building Circularity Indicator assessment model

The following solutions to the limitations of assessing disassembly potential are proposed in the new BCI assessment model:

- The building level of all materials and products in the BOM are determined. A classification method to do this is proposed in this research based on existing methods.
- Detail drawings are used to develop relational patterns which serve as framework to assess the disassembly potential. A distinction is made between technical factors that asses the product disassembly potential and the connection disassembly potential.
- Twelve most important of the twenty-five disassembly factors are incorporated in the model based on testing the importance of factors with experts in the field and comparing the results with existing research
- By incorporating process-based factors as preconditions and financial based factors as drivers. These can be used to consider disassembly in the building development process.
- No significant difference between the results of weighted disassembly factors and the baseline model (equal weight) is found. Therefore the decision is made to use equal weights for disassembly factors in the BCI assessment model.
- The Disassembly potential of products (PCI) and systems (SCI) are assessed. Products can be part of systems and vice versa. The relations between different products, different systems and between products and systems are incorporated in the model. This integrates a system way of thinking.
- By grouping products into reusable systems and determining the disassembly potential of these, the goal of material reutilization is actively integrated in the model. Another option to use a disassembly threshold is given.

4.1.1. Method for building the BCI assessment model

Building the model is an iterative process of trial-and-error by applying different theories in the assessment model. During the model different parameters are changed, cases are tested and results are interpreted. The goal is to solve the limitations identified in this research. The results and decisions are explained step-by-step. The model is tested for validity after the conceptual model is developed.

4.1.2. Method for testing the validity of the BCI assessment model

The method to assess the disassembly potential is revised which has an influence on all the steps in the BCI. Models are used to predict or compare the future performance of a new system, a modified system, or an existing system under new conditions. (Carson, 2002) There are several ways to validate a model:

- Test for face validity (does the model to what it is expected to do?);
- Changing the input parameters (what do different values for factors do and what do different scenario's do?)
- Comparing the model with past performance or to a base-line model. (How does the new method perform compared to the old method?)

During the development of the conceptual model, different parameters have already been tested and applied, for instance changing the fuzzy variables to better fit the assessment model (Appendix 7) and by testing the influence of different weights for disassembly factors. (chapter 3.3.4.3)

The validation will be performed with a case study. The case study acts to test face validity by testing input parameters with a real building project. These results are compared with practical experience of the developers of the project that serves as case study to validate whether the results represent the reality.

The same case study is assessed with the old BCI assessment model. This will serve to compare the performance of the new model with the base-line model. This will give an overview of the differences and the impact the new BCI assessment model has on the results.

4.2. Building the new BCI assessment model

4.2.1. Implementing the new disassembly factors

First of all twelve disassembly factors are implemented in the new BCI assessment model (Table 18) These disassembly factors are validated to be important. A hypothesis was made that the weight of disassembly factors vary. This cannot be concluded from this research and equal weights are adopted

Table 18: Technical, Process-based and financial-based factors for disassembly

Type of factor	Disassembly factor	Weight
Technical	Independency	1.00
	Type of relational pattern	1.00
	Assembly sequences	1.00
	Assembly shape	1.00
	Method of fabrication	1.00
	Type of connection	1.00
	Accessibility to connection	1.00
Proces	Deconstruction safety	1.00
	Disassembly instructions	1.00
	Number of operations	1.00
	Disassembler expertise	1.00
Financial	Disassembly costs	1.00

The disassembly factors are categorized according to the IPF-model to relate them to the different types of KPI's identified in the BCI assessment model. (Chapter 2.6.3) (Table 19)

- Technical factors are incorporated as technical requirements
- Process-based factors are incorporated as preconditions
- Financial-based factors are incorporated as drivers

Table 19: Technical requirements, preconditions and drivers for disassembly

Technical requirements	Preconditions	Drivers
Accessibility to connection	Deconstruction safety	Disassembly costs
Type of connection	Disassembly instructions	
Assembly shape	Disassembler expertise	
Independency	Number of operations	
Method of fabrication		
Assembly sequences		
Type of relational pattern		

Technical disassembly factors are incorporated in the calculation model to assess the disassembly potential. Preconditions and drivers can be assessed with independent tools that are not included in the Building Circularity Indicator assessment model. Or they can be used to guide the building development process.

4.2.2. Technical requirements for building disassembly

The implemented technical factors for disassembly origin from the Disassembly Determining Factors (Durmisevic, 2006) These variables have attribute values based on the fuzzy set theory which are adopted to assess the factors in the BCI assessment model. This research aimed to determine relative weights between factor. Assessing new attribute weights for disassembly factors was out of the scope because this was already researched thoroughly.

4.2.1.1. Independency

Independency is an adaption of the factor functional dependence (Durmisevic, 2006). Decoupling components is desirable (Hassanain & Harkness, 1997) but when systems are grouped this should be done as much according to functional and physical interactivity as possible (Wang et al., 2014). Incorporation and interpenetration of different components lead to dependency which influences the integrity of components (Durmisevic, 2006). Disassembly is aimed to reuse and when the integrity is compromised due to disassembly, it can be said that the disassembly potential is less. (Ciarimboli & Guy, 2005). during the design, interpenetration of different products and incorporation of components together in build ups should be avoided, securing independency. Five attributes to determine whether a independency is secured are determined. When assessing the factors, the total buildup is considered. Figure 30 and Table 20 show how this is done.

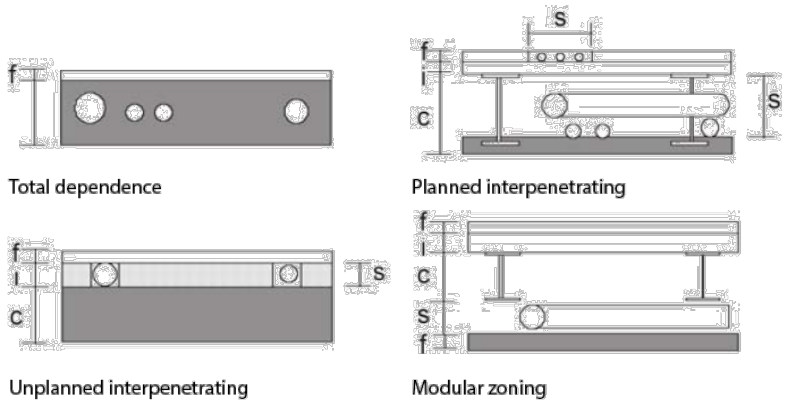


Figure 30: Different levels of independency based on the fuzzy variables (Durmisevic, 2006)

Table 20: Fuzzy values for independency based on the fuzzy variables (Durmisevic, 2006)

Independency	Modular zoning	1.0
	Planned interpenetrating for different solutions (overcapacity)	0.8
	Planed for one solution	0.4
	Unplanned interpenetrating	0.2
	total dependence	0.1

4.2.1.2. Type of relational pattern

The type of relational pattern assesses an assembly as an entity and considers whether it is hierarchically structured or if it is horizontally structured. When products are connected with multiple other products, the assembly structure becomes horizontal. Less connections lead to a hierarchical structure. More connections lead to the requirement to disassemble more connections, making disassembly potential lower. Because the BCI assessment model is aimed to assess individual products, the adaption is made to regard the amount of connections per product to integrate this factor. For each product the amount of connections with other products is counted. In appendix 7 the reason and impact for changing the original fuzzy variable categories are explained.

Table 21: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Type of relational pattern	One or two connections	1.0
	Three connections	0.6
	Four connections	0.4
	Five or more connections	0.1

4.2.1.3. Assembly sequence

Most researchers combine disassembly sequencing with disassembly direction. Durmisevic (Durmisevic, 2006) argues a differentiation where lower component levels should follow up on higher component levels during assembly. Because the assembly sequence determines in which sequence should be disassembled. (Hassanain & Harkness, 1997; Lambert & Gupta, 2005) In product design assembly sequencing is used to split mechanical and electrical components. (Thormark, 2001) and it is a determinant factor to decrease disassembly time (Peeters et al., 2012) It is easier to take out smaller products. When components of the same level are connected with each other, it rules out relations with other building levels which makes disassembly harder.

Table 22: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Assembly Sequence	Same level / Same level	1,0
	High level / Low level	0,5
	Low level / High level	0,1

4.2.1.4. Assembly shape

Assembly shape is an adoption of the factor geometry of product edge. The geometry of product boundaries (shape) can lead to open or interpenetrating geometry. This is influenced by interface design and the specification of the connection type. (Durmisevic, 2006) Assessing this factor relates to the product and the direct surrounding of the product edges. Figure 31 and

Table 23 show how this is assessed.

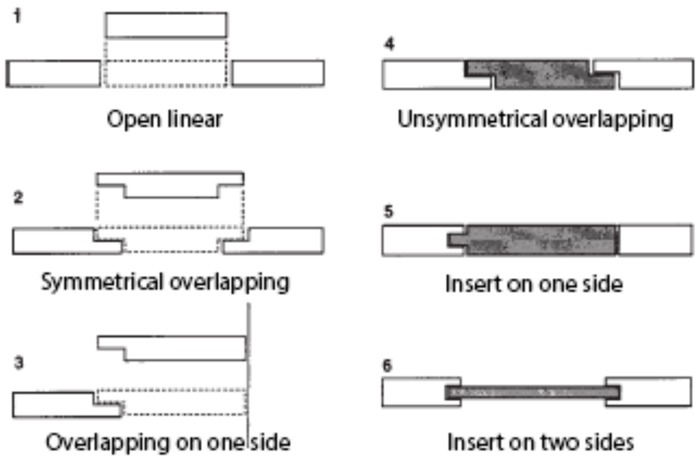


Figure 31: Different levels of independency based on the fuzzy variables (Durmisevic, 2006)

Table 23: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Assembly shape	Open linear	1
	Symmetrical overlapping	0,8
	Overlapping on one side	0,7
	Unsymmetrical overlapping	0,4
	Insert on one side	0,2
	Insert on two sides	0,1

4.2.1.5. Method of fabrication

Method of fabrication is an adoption of the factor standardization of product edge. The method of fabrication describes whether a product or assembly is prefabricated or build on the construction site. (Durmisevic, 2006) Beside making the products more reusable, (Akanbi et al., 2018) prefabrication leads to easier disassembly due to standardization of connections (Durmisevic, 2006), easier accessible connections (Rios et al., 2015) and the ability to disassemble complete components on-site and further separation of components off-site. (Ciarimboli & Guy, 2005) Because in the end every product is made in an industrial process, the method how this is processed in an assembly determines how it is assessed.

Table 24: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Method of fabrication	Pre-made geometry	1
	Half standardised geometry	0,5
	Geometry made on the construction site	0,1

4.2.1.6. Type of connection

The type of connection does not assess the product but the connections between products. For every connection an assessment can be made in which category it falls. Appendix 7 also includes examples of different connection types that are commonly used in building engineering to use as a reference.

Table 25: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Type of connection	Accessory external connection or connection system	1
	Direct connection with additional fixing devices	0,8
	Direct integral connection with inserts (pin)	0,6
	Filled soft chemical connection	0,2
	Filled hard chemical connection	0,1
	Direct chemical connection	0,1

4.2.1.7. Accessibility of connection

Accessibility to connections refers to physically being able to access the connections between products without demolishing (parts) of the product. (Durmisevic, 2006) This influences the reusability of the product and surrounding products, but also makes the dismantling process easier and quicker. (Ciarimboli & Guy, 2005; Peeters et al., 2012; Rios et al., 2015; Soh et al., 2014; Thormark, 2001) for each product and connection an assumption has to be made which category is applicable. This depends on the surrounding products and the product to be assessed itself.

Table 26: Fuzzy values for Type of relational pattern based on the fuzzy variables (Durmisevic, 2006)

Accessibility to connection	Accessible	1
	Accessible with additional operation which causes no damage	0,8
	Accessible with additional operation which is reparable damage	0,6
	Accessible with additional operation which cases damage	0,4
	not accessible - total damage of elements	0,1

4.2.2. Preconditions for disassembly

Preconditions give organizations options to include in their procurement for which a building or process has to comply. (Verberne, 2016) When an organization includes a precondition for circularity, the process has to meet the preconditions.

4.2.2.1. Deconstruction safety

Deconstruction safety is part of the disassembly process at the end-of-lifecycle of a building. There is regulation regarding building and demolishment safety plans. (Hoogervorst, 1999) in bouwbesluit 2012 (Artikel 8.7 Veiligheidsplan, Bouwbesluit 2012) there is a guide for developing a construction and demolishment safety plan. Safety for deconstruction falls in this category but it does not specifically mention deconstruction instead of demolishment. Maybe deconstruction requires more extensive safety measures due to the nature of deconstruction activities. This is not covered in this research. To enable the feasibility of deconstruction, the requirement of extensive environmental health and safety protections should be avoided. (Ciarimboli & Guy, 2005) This is usually established through design decisions (technical factors). Deconstruction safety is regarded as a precondition because during the development of the building, the organization can opt in their procurement phase that special attention has to be paid to guarantee that extensive health and safety protections are not necessary at the end of the lifecycle of a building through careful planning and decision making, making disassembly more viable.

4.2.2.2. Disassembly instructions

Disassembly can be regarded as a reverse process of assembly. Assembly instructions are normal procedure, especially since products became more complex. In the building industry a design is made which essentially functions as assembly instructions. During the building process a lot of things are sensitive to change. As-built drawings are developed to reflect all changes made during the construction process and contain the real time geometry, locations and measurement. They are developed at the end of the construction (realization) phase. (Clayton, Johnson, Song, & Al-Qawasmi, 1998) A deconstruction plan is now usually related to safety issues regarding deconstruction but this is covered in chapter 4.2.2.2. Disassembly instructions can help in overcoming process-based challenges and communicate specific technical interventions to enable disassembly at the end of the lifecycle of a building. This will ease the deconstruction process and therefore make it more feasible. (Thormark, 2001) It is considered as a precondition for disassembly in this research because when an organization preconditions the development of disassembly instruction for their building, the process will be made easier, helping disassembly potential at the end of lifecycle of a building. it is not a technical requirement. A building can perfectly be disassembled without instructions if it is sufficiently fit for disassembly through technical factors. It is also not a financial driver because the benefit between having instructions and not having instructions is not easily translatable to money.

4.2.2.3. Disassembler expertise

There is a difference between demolishment activities and disassembly activities. Connections can be complex and the experience of the construction worker may be insufficient, leading to demolishment instead. (Soh et al., 2014) The expertise of the disassembler is regarded as a precondition because an organization can require the deconstruction contractor that they have experience with disassembly instead of demolishment. Expertise is considered an important factor by deconstruction experts.

4.2.2.4. Number of operations

The number of operations required is not entirely a standalone factor. Every operation necessary to disassemble a component is the result of required tools, type of connection, accessibility of connection, etc. Because it reflects the complexity the disassembly process (Ciarimboli & Guy, 2005) it is considered as a process-based factor but it closely related to design and financial-based factors. Reducing the number of operations can also be achieved by carefully planning disassembly operations.

4.2.3. Drivers for disassembly

Financial drivers stimulate the circular economy. They can be seen as value proposition. A financial value is a “harsh and objective” language that humans can translate to. They can be used in a process to gain further insights in potential (financial) risks. (Verberne, 2016)

4.2.3.1. Disassembly costs

Disassembly costs is the major financial driver for disassembly instead of demolishment. Costs may be a hinderance to deconstruction. There is a common perception that cost pertaining to deconstruction is greater than demolition and disposal. However, studies had shown that it is not always true. (Rios et al., 2015) Costs for deconstruction are now always dedicated to the end of the lifecycle. DfD recognizes that the “upfront, operating and back-end” costs in providing the services of the built environment should be considered in the initial building design. (Ciarimboli & Guy, 2005) This would shift responsibilities for costs to other stakeholders. There are many things influencing disassembly costs. Compared to demolishment, where disposal of material is an expense, potential residual value of disassembled materials can help in cutting the costs for disassembly.

4.2.4. New Material Circularity Indicator (MCI)

The Material Circularity Indicator in the BCI assessment model (Verberne, 2016) is an adoption from the Material Circularity Indicator (Ellen MacArthur Foundation & Granta Design, 2015) represented in Figure 32. A complete overview of the Building Circularity Indicator assessment model by Verberne (2016) can be found in Appendix 1.

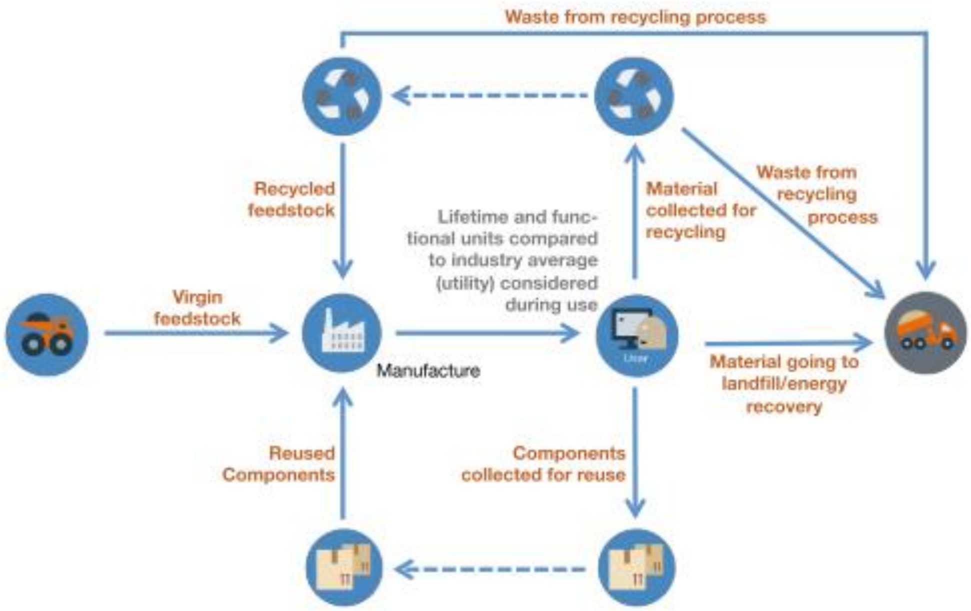


Figure 32: Material Circularity Indicator (Ellen MacArthur Foundation & Granta Design, 2015)

A product is built up using a number of components, sub-assemblies, parts, and/or materials. Depending on the level of detail, a Bill of Material (BOM) can frame all materials. Based on all the sub-assemblies, parts, and/or materials (χ), the Material Circularity Indicator can sum up all material input. (Verberne, 2016) No changes are made in the calculation method thus the Material Circularity Indicator will still be calculated according to Appendix 1.

Which is:

$$MCIp(\alpha) = max\ (0, (1 - LFIp(\alpha) \cdot F(Xp(\alpha))))$$

Where
$LFIp(a)$ is the Linear Flow Index (from the Virgin Feedstock and Waste);
$F(Xp(a))$ is the function of the utility factor $Xp(a)$;

Chapter 2.6.2 explains the theory of building levels and It is an important strength to be able to assess the MCI on any building level. The input determines on which building levels the BCI is calculated.

4.2.4.1. Assessing the building levels in the MCI

To maintain the flexibility of having the level of detail of the BOM influence the input, an additional assessment to classify the input on a scale of building levels is required. This will not influence the calculation method for disassembly in the new Building Circularity Indicator assessment model.

There are several methods to define the building levels to be considered. Two widely used methods in the Dutch industry are the NL/SfB (BNA, 2005), which defines categories and a coding system to determine building levels. And the STABU2 method (STABU, 2015), which also defines categories and a coding system. Using a coding system that is comprehensive and transparent is preferred. In Appendix 6, different classification methods are compared and a decision is made to adopt a classification method in this research which is shown in Table 27.

Because there is no standard method that includes all building levels, a combination of methods is used. This results in using two different coding methods which is not an ideal situation. The first four building levels are determined by the six digit categorization by the NL/SfB (BNA, 2005). This makes the System, Element group, Element and product level objectively distinguishable. Everything lower has to be categorized with the STABU2 method (STABU, 2015).

The STABU2 method is not open source. In this research an estimation is made based on the situation of the assembly when a building part is categorized as 'component level' or 'material level'. The differentiation between levels is said to be relative to the situation (Durmisevic, 2006) which already implies a certain degree of uncertainty in every situation. In practice it is difficult to obtain data on a very high detail level (component or material). Therefore it is expected that this is not frequently applied. (Hijazi & Omar, 2017) However to make the BCI applicable on any scale it has to be covered in this research. It is recommended that a universal open standard is developed and adopted in the Building Circularity Indicator assessment model. Adding this will lead to the requirement to classify all input from the BOM.

Table 27: Classification methods and adopted definitions

Level	Source	Adopted definition	Example coding	Example description
0	Layers of Brand	Building layers		Space plan
1	NL/SfB (2 digit coding)	System level	22	Interior wall
2	NL/SfB (3 digit coding)	Element group level	22.1	Non-structural
3	NL/SfB (4 digit coding)	Element level	22.13	Fixed partition wall
4	NL/SfB (6 digit coding)	Product level	22.13.17	Metal stud wall, plasterboard
5	STABU2 (specification group)	Component level	44.41.21-X	Plasterboard
6	STABU2 (specification group)	Material level	44.41.21-X	Plasterboard
7		Raw material		Gypsum

4.2.5. New Product Circularity Indicator (PCI)

The Material Circularity Indicator is based on the assumption that the summation of all MCI_p's is the total circularity index of a building. However, this is not realistic because the interfaces and connections between these products are important for indicating the circularity of a system. The MCI_p is regarded to be the theoretical value of the product and the PCI_p is the practical value where these connections and interfaces are included in the value. (Verberne, 2016)

The Product Circularity Indicator (PCI) is calculated with the Material Circularity Indicator (MCI) and the Disassembly Potential (DP).

$$PCI_p = MCI_p \cdot DP_p$$

In which
PCI_p= Product Circularity Indicator for product p.
MCI_p= Material Circularity Indicator for product p.
DP_p= Disassembly Potential for product p.
The Disassembly Potential of every product can be calculated with the following method:

$$DP_p = \frac{1}{\omega_d} \cdot \left(\sum_{j=1}^{n} \omega_j \cdot PD_{jp} + \sum_{j=1}^{n} \omega_j \cdot CD_{jp} \right)$$

In which:
DP_p= Disassembly potential of product p.
ω_j= Weight of disassembly factor j.
ω_d= Total weight of disassembly factors.
PD_{jp}= Product Disassembly potential of factor j for product p.
CD_{jp}= Connection Disassembly potential of factor j for product p .

ω_d is calculated with:

$$\omega_d = \sum_{j=1}^{n} \omega_j$$

PD_{jp} is calculate with:

$$PD_{jp} = \min\left(PD_{jpk}\right)$$

In which:
PD_{jpk}= Product Disassembly Potential of factor j for product p of all assemblies k.

CD_{jp} is calculate with:

$$CD_{jp} = \min\left(\sum_{j=1}^{n} CD_{jck}\right)$$

In which:
CD_{jp}= Connection Disassembly Potential of factor j for connection c of all connections k.

4.2.5.1. Disassembly factors in the new BCI assessment model

To assess the new factors for disassembly, the fuzzy variable categories are again adopted (Durmisevic, 2006) as mentioned in chapter 4.2.2. The weights for the disassembly factors are equal because the derived weights do not significantly influence the results. (chapter 3.3.4.3) Table 28 shows a complete overview.

Table 28: Disassembly factor weights and attribute weights adopted from Durmisevic (2006)

Disassembly factor	Factor weight	Attribute	Score
Accessibility to connection	1.0	Accessible	1.0
		Accessible with additional operation which causes no damage	0.8
		Accessible with additional operation which is reparable damage	0.6
		Accessible with additional operation which cases damage	0.4
		not accessible - total damage of elements	0.1
Type of connection	1.0	Accessory external connection or connection system	1.0
		Direct connection with additional fixing devices	0.8
		Direct integral connection with inserts (pin)	0.6
		Filled soft chemical connection	0.2
		Filled hard chemical connection	0.1
		Direct chemical connection	0.1
Assembly shape	1.0	Open linear	1.0
		Symmetrical overlapping	0.8
		Overlapping on one side	0.7
		Unsymmetrical overlapping	0.4
		Insert on one side	0.2
		Insert on two sides	0.1
Independency	1.0	Modular zoning	1.0
		Planned interpenetrating for different solutions (overcapacity)	0.8
		Planed for one solution	0.4
		Unplanned interpenetrating	0.2
		total dependence	0.1
Method of fabrication	1.0	Pre-made geometry	1.0
		Half standardised geometry	0.5
		Geometry made on the construction site	0.1
Assembly Sequence	1.0	Same level / Same level	1.0
		High level / Low level	0.5
		Low level / High level	0.1
Type of relational pattern	1.0	One or two connections	1.0
		Three connections	0.6
		Four connections	0.4
		Five or more connections	0.1

The factors ‘type of connection’, ‘assembly sequence’ and ‘type of relational pattern’ are modified because the fuzzy variables of the factors do not suit the proposed calculation method. The adaption is shown in this table and is explained in appendix 7. Further research is necessary to validate the weighting of the attributes of these factors.

4.2.5.2. Detail drawing as input to create relational patterns

The input data required to assign attributes to products is obtained from the BOM (Verberne, 2016). Every product is individually assessed based on the DDF’s. This leads to an assessment for each product in isolation of other products while originally the DDF’s consider an assembly of the products which includes the relations of product with each other. (Durmisevic, 2006). This research proposes using a relational pattern to assess disassembly.

A product on any level is always connected with other products. By considering an assembly as a whole to assess the disassembly potential, all individual connections and products are included in the assessment. To do this, a relational pattern is developed from a detail drawing. The relational pattern represents the products and the connections, which is used to determine the input for the disassembly factors.

The detail drawing is a two-dimensional technical representation of a specific junction in a building. It can be regarded as an instruction for assembly. This input is used in the research by Durmisevic (2006) to represent the relational pattern. When using the detail drawings as method to define relational patterns, all most important junctions can be assessed for disassembly potential. Very specific variations can be disregarded or included, depending on how many times it is repeated or how different the assembly is.

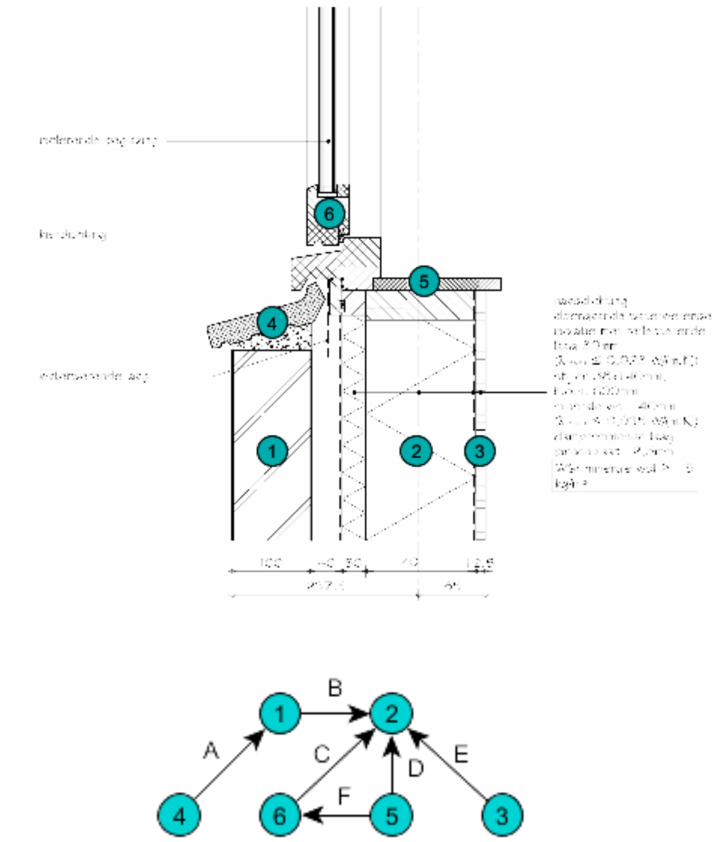
By including the most important junctions, the majority of the building is covered in the assessment model. A standard assessment for the most important detail drawings does not exist. However when considering a building, junctions where different functions (shearing layers of Brand (Brand, 1994)) intersect can be regarded as important. The building development team should decide together what the most influencing detail drawings are to make an accurate assessment for the projects disassembly potential.

The detail drawing limits the assembly that is considered. Products can however appear in multiple detail drawings with different assemblies. This is not an issue with this calculation method. When a product is coded the same in all assemblies, a Bill of Disassembly Potential is developed.

The example used to present the results of the new calculating method is a standard detail drawing of a window frame in a housing project retrieved from SBR (SBRCURnet, 2015). This example is not part of a building that is designed to be disassembled. The reason for using this example is because it is one of the most common detail drawings and is easy to interpret.

4.2.5.3. Relational pattern as a method to assess disassembly potential

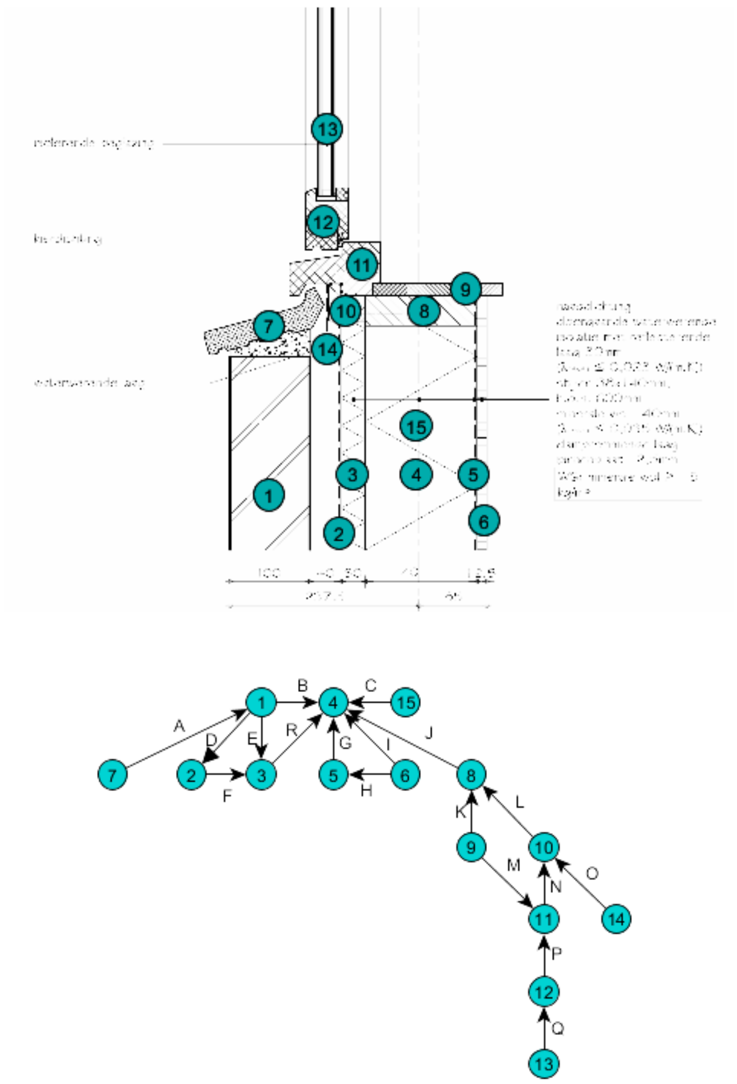
The complexity of the relational pattern depends on the detail level of the BOM. A theoretical example of this is shown in Figure 31.



Part	Description	Level
1	Brick wall	Product
2	Timber frame construction	Product
3	Plasterboard	Component
4	Exterior window sill	Component
5	Interior window sill	Component
6	Window turn-only	Element

Figure 33: Relational pattern of a detail drawing (SBRCURnet, 2015) *with a low level of detail to represent an assembly of products.*

This detail drawing is a commonly used example in the built environment for a window frame. The building level of each product is determined based on Table 27. A combination of levels like components and elements in the same assembly is no problem. It is also possible that the BOM is very detailed which results in a more complicated relational pattern for the same assembly. (Figure 34)



Part	Description	Level
1	Brick wall	Product
2	waterproof layer	Material
3	Insulation	Component
4	Vertical timber framing	Product
5	Vapor barrier	Material
6	Plasterboard	Component
7	Exterior window sill	Component
8	Timber framing	Product
9	Interior window sill	Component
10	Mounting frame	Material
11	Window frame	Component
12	Window profile	Component
13	Double glazing	Component
14	waterproof layer	Material
15	Insulation	Component

Figure 34: Relational pattern of a detail drawing (SBRCURnet, 2015) *with a high level of detail to represent an assembly of products.*

4.2.5.4. Assessment model for disassembly potential

This method for calculating the Disassembly potential will enable the assessment of all products and all related connections to that product. To do this, the input for the disassembly factors are assigned to either to product or the connection. Table 29 and Figure 35 show an example of the application of this by assessing the brick wall in the relational pattern of Figure 33.

Table 29: Overview assignment disassembly factors with product or connection

Disassembly Factor	Type of factor
Accessibility to connection	Connection disassembly factor
Type of connection	Connection disassembly factor
Assembly shape	Product disassembly factor
Independency	Product disassembly factor
Method of fabrication	Product disassembly factor
Assembly sequences	Connection disassembly factor
Type of relational pattern	Product disassembly factor

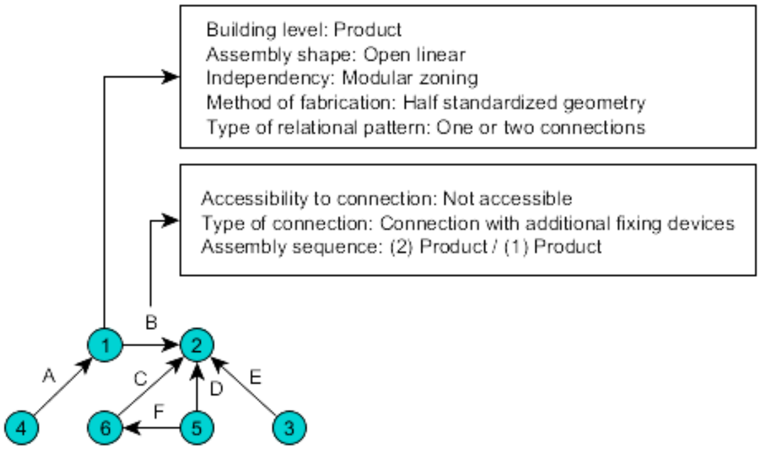


Figure 35: Relational pattern with attributes for disassembly potential

The product disassembly factors are assessed in relation to the surrounding products in the assembly. The weights of the disassembly factors and the resulting attribute weights are adopted from Table 27. These can be different for every assembly for which the product is considered in. By coding the products consequently the same a 'Bill of Product Disassembly factors' is created that represents all scenario's and resulting product disassembly weights for all products.

The lowest score for a product disassembly factor of all assemblies that the product appear in is considered in the calculation model. The pattern is only used to limit the assembly. The product disassembly factors are a property of the product. When a product is for instance 'open' in one assembly, but 'inserted' in another assembly, the product disassembly factor to consider in the calculation is 'inserted'. Because it does not matter when in one assembly it is open, to disassemble the product the inserted part still exists.

The connection disassembly factors are also assessed in relation to the surrounding products. A product can have multiple connections. The arrows in the relational pattern represent the sequence of assembly. The product with an incoming arrow acts as the bearing product for the other. The connections considered for the disassembly potential of a product are the outgoing connections. It is assumed, when the product is disassembled, all underlying products already have to be disassembled. A theoretical example of this is shown in Figure 35. The outgoing connections (red) are determinant for the disassembly potential of product "2".

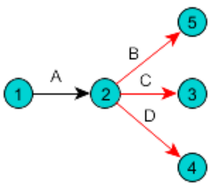


Figure 36: Outgoing connections determine the disassembly potential of the product

When a product has no outgoing connections this means that it not connected with anything in that specific assembly.

When there are multiple connections towards bearing products, the worst connection is considered for the calculation method. So unlike the product disassembly factors, the lowest total connection disassembly potential is used. The theoretical example in Figure 37 shows this.

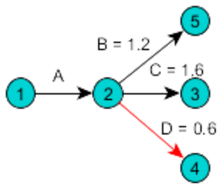


Figure 37: The lowest disassembly potential is considered for the calculation

A Bill of Disassembly potential for every product is created by assigning a unique ID to every product. All assemblies are included this way. An example of assessing the disassembly potential of a product is shown in Figure 38 and Table 30.

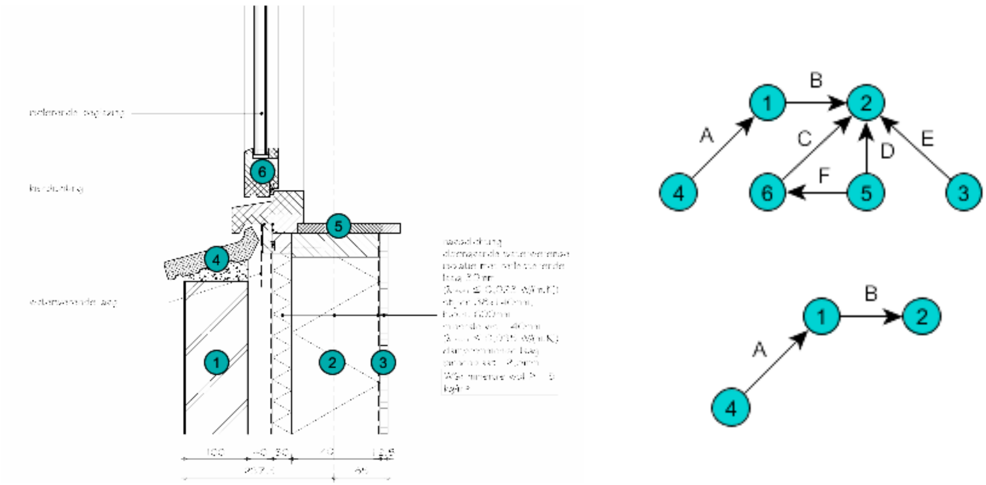


Figure 38: Example of assessing the Product Disassembly Potential and the Connection Disassembly potential (detail drawing, (SBRCURnet, 2015)

Table 30: Example of assessing the Product Disassembly Potential and the Connection Disassembly potential

Product Disassembly factors	Factor weight	Description	Score
Product ID		1	
Assembly ID		1	
Node ID		1	
NL/SfB code		21.11.11	
Building level		4: Product	
Assembly shape		Open linear	1.0
Independency	1.0	Planned for one solution	0.4
Method of fabrication	1,0	Geometry made on construction site	0.1
Type of relational pattern	1.0	One or two connections	1.0
Product disassembly potential			2.5

Connection Disassembly factors	Factor weight	Description	Weight
Connection ID		B	
Product (1)		2	
Product (2)		1	
Accessibility to connection	1.0	Not accessible	0.1
Type of connection	1.0	Connection with additional fixing devices	0.4
Assembly sequence	1.0	Product (2) / Product (1)	1.0
Connection disassembly potential			1.5

Total disassembly potential	0.57

The disassembly potential is 0.57 which is multiplied by the MCI of that product. The PCI regarded on building level 4: Product.

4.2.6. New System Circularity Indicator (SCI)

The System Circularity Indicator for each system can be calculated with the following method:

$$SCI_s = MCI_s \cdot DP_s$$

In which:
SCI_s= Product Circularity Indicator for system s.
MCI_s= the aggregation of the Linear Flow Index and the Utility Factor for all products in a system. (Appendix 1)
DP_s= The disassembly potential of the system.

The SCI_s differs from the $SCI_{s(p)}$ (Verberne, 2016) The systems are not categorized by layers of Brand and the normalizing factor is not included in this step of the calculation method. Instead, systems are either formed by determining a disassembly possibility threshold or by determining the reusability of the system. Both the PCI_p and SCI_s are calculated with the Disassembly potential.

4.2.6.1. Methods for categorizing systems

Products are categorized according to the shearing layers of Brand, Normalized factors are used to determine a weighted average of each product towards the SCI. The factor mass is chosen. This factor is disputable and other proposals are also arguable like sales revenue, number of materials, volume, etc. (Verberne, 2016) This method of determining the SCI disregards connections between shearing layers and is not in line with a system way of thinking.

Alba Concepts determines Elements instead of Systems. Elements are composed one or more products that cannot be disassembled from each other. The disassembly factor accessibility to connection is used to determine this. (Appendix 5) This method is in line with a system way of thinking but is sensitive to subjectivity and dismisses low scoring connections from the calculation, creating an overly positive result.

This research adopts relational patterns as a framework to assess disassembly potential. This makes is possible to determine systems more accurately than using the layers of Brand (Verberne, 2016) or only one disassembly factors to group products together. This promotes a system way of thinking because the relations between products and systems are considered in the calculation. This is a principle of the circular economy. (Ellen MacArthur Foundation, 2013)

Two methods are proposed to group products together into systems and are explained.

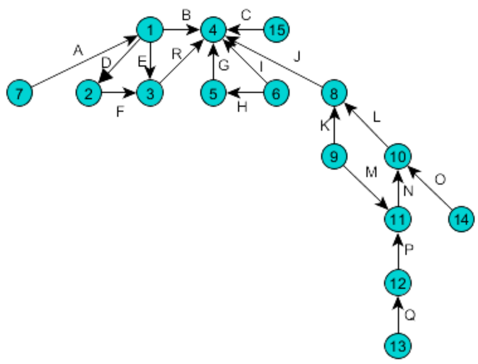
- Using a Disassembly Potential threshold to group products in a system. This is still creates bias towards a positive result but can be used to correct low scores when data is determined on low building levels. (5 and 6)
- Using reusability potential to group products together. This is preferred because it incorporates reusability which is the goal of disassembly. Reusability is out of the scope of this research so this is based on assumptions and no framework can be provided for this.

4.2.6.2. Using disassembly threshold as a method to determine systems

When the disassembly potential of a product is lower than a certain threshold, it can be considered that it is impossible to disassemble without implications for that, or surrounding products. By testing the case study and the examples used to explain the calculation method, the threshold for disassembly potential is set on $DP\alpha = 0.6$. Table 31 shows the assessment of the disassembly potential of all products in the detail drawing of a window frame (SBRCURnet, 2015).

Table 31: Disassembly potential of all products. (limited to one detail drawing)

ID	Description		Disassembly potential DP_p
1	Brick wall	Product	0.39
2	waterproof layer	Material	0.44
3	Insulation	Component	0.36
4	Vertical timber framing	Product	-
5	Vapor barrier	Material	0.43
6	Plasterboard	Component	**0.69**
7	Exterior window sill	Component	**0.73**
8	Timber framing	Product	**0.60**
9	Interior window sill	Component	**0.61**
10	Mounting frame	Material	0.50
11	Window frame	Component	0.49
12	Window profile	Component	**0.93**
13	Double glazing	Component	**0.84**
14	waterproof layer	Material	0.46
15	Insulation	Component	0.49



The products and the related connections that have a disassembly potential below the threshold DPα = 0.6 form systems. Figure 39 is a schematic representation of products that are connection with each other that are regarded impossible to disassemble.

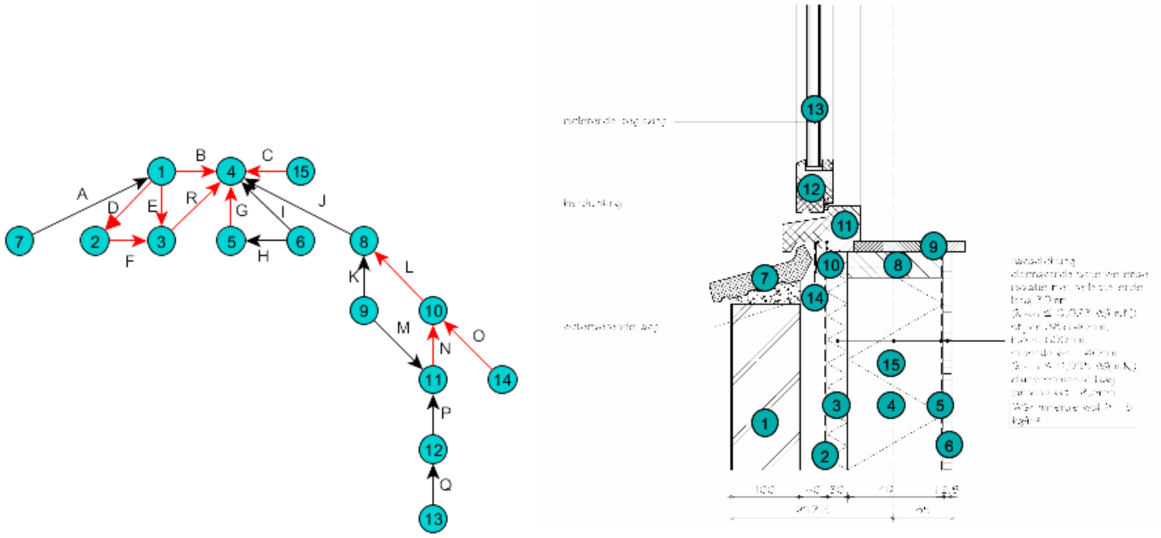


Figure 39: Relational pattern with high disassembly potential (DPα ≥ 0.6; black arrow) and low disassembly potential (DPα ≤ 0.6; red arrow).

With this method, systems are defined to be all groups of products that are connected with each other. By grouping these together and splitting them in a relational pattern, a schematic representation is once again developed. The relational pattern considers individual products as well as systems.

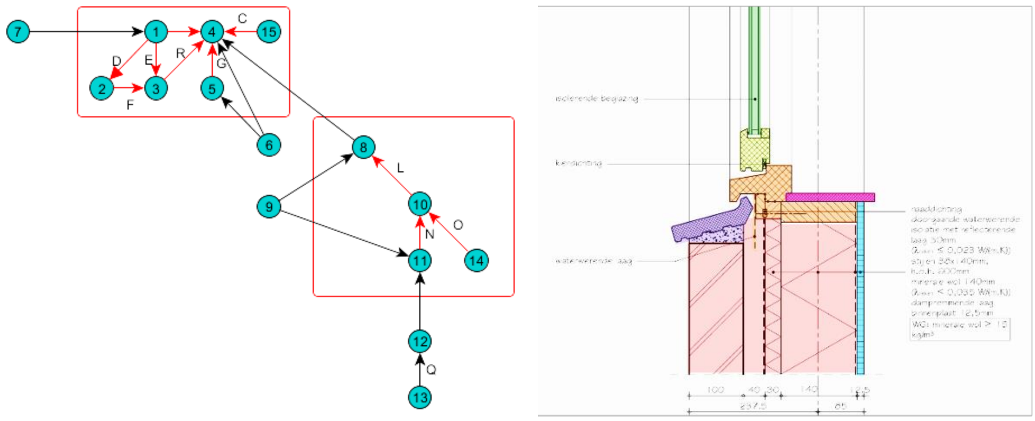


Figure 40: Systems with a low disassembly potential split from each other in a relational pattern and a visual representation of the systems in a detail drawing. Detail drawing retrieved from SBR (SBRCURnet, 2015)

The systems are individually assessed for disassembly potential according to the Disassembly Potential calculation method. The determined systems in Figure 40 are compared with the same assembly in which products are determined on a higher building level.

ID	Disassembly potential
1	**0,58**
2	-
3	0,69
4	0,76
5	0,60
6	0,63

ID	Disassembly potential
S1	-
S2	0,76
S3	0,76
S4	0,61
S5	**0,30**
S6	0,93
S7	0,84

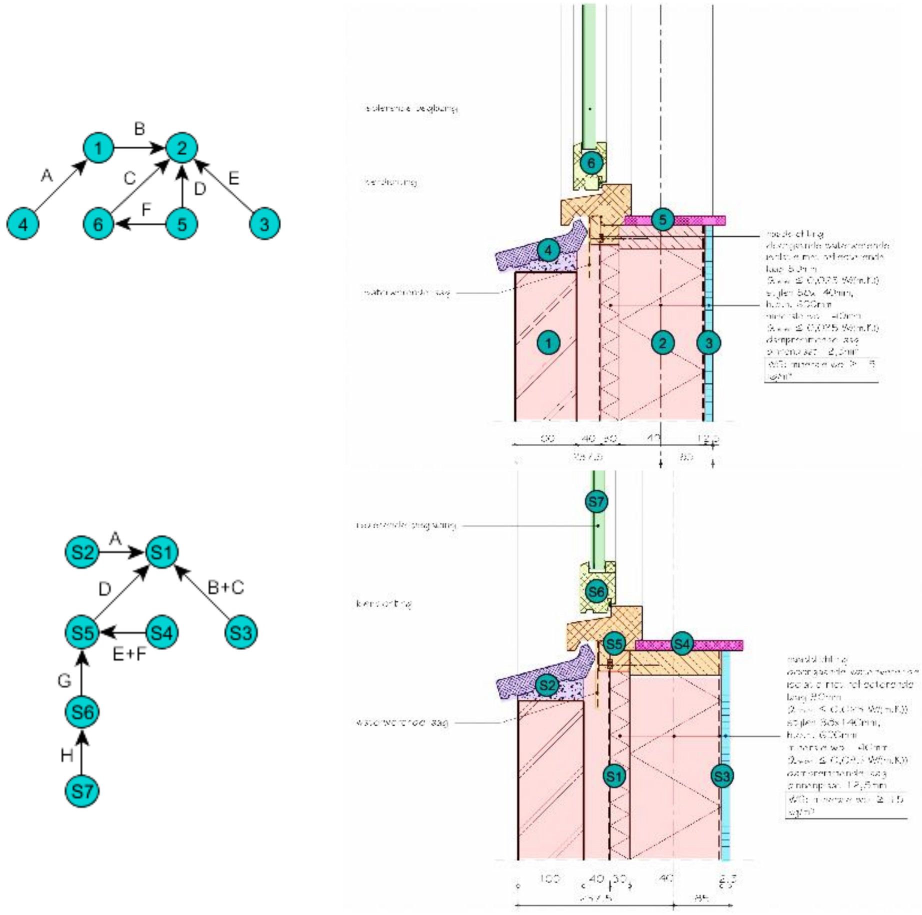


Figure 41: Comparison of disassembly potential of the same assembly on two different building levels. Detail drawing retrieved from SBR (SBRCURnet, 2015)

The defined systems are comparable with the defined products on a higher building level. This method can be used to correct low scores when the input is defined on a low building level (5&6) to compare the results with buildings on a higher building level.

4.2.6.3. Reusability as method to assess systems

Material reutilization is the goal and disassembly is one of the influential factors that enables this. (Chapter 2.6.4) When using a disassembly threshold, the SCI assesses the highest level of disassembly potential. The systems represent which parts of a building can be disassembled but this does not mean these systems are reusable as an entity.

There are several material reutilization strategies. Short reuse cycles are preferred in the circular economy. This research considers disassembly for retain, refit, refurbish, reclaim/reuse and remanufacture. This means that recycling is disregarded as disassembly is not the most important factor to enable recycling but the technical limitations to recycling are a more important obstacle for different products to overcome. (Schneider & Ragossnig, 2014)

Table 32: Material reutilization strategies compared to building levels

	Ladder van Lansink (Lansink, 1979)	Circular Economy (Cheshire, 2016)	Building levels new BCI assessment model
Circular Economy	Prevention	Retain	Building layers
		Refit	System level
	Reuse	Refurbish	Element group level
		Reclaim/reuse	Element level
		Remanufacture	Product level
			Component level
			Material level
	Recycle	Recycle/compost	Raw material level
Linear Economy	Energy recovery	Energy recovery	
	Incineration		
	Landfill	Landfill	

It is possible to group systems by reusability. Doing so will result in an overview of the disassembly potential of reusable systems and then disassembly potential can be used to assess critical connections that have a low disassembly potential. Reusability potential is out of the scope of this research but an example of using reusability together with disassembly is developed based on assumptions to show the process. (Figure 42)

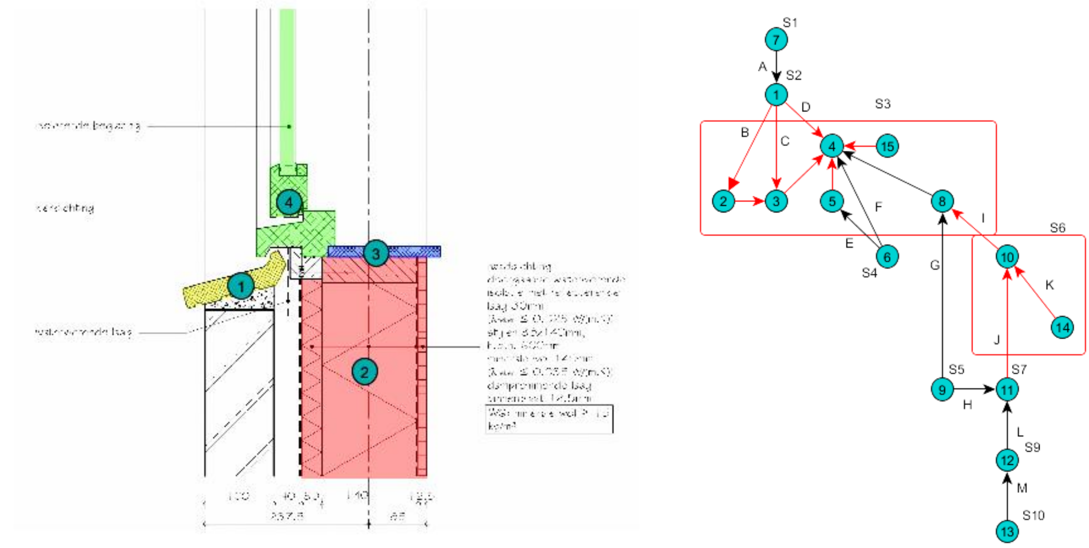


Figure 42: Assessment of the Disassembly potential of reusable systems. Detail drawing retrieved from SBR (SBRCURnet, 2015)

First the reusable systems are identified in an assembly. Based on this the relational pattern is once again developed. It is also possible to adapt the relational pattern determined with the threshold for Disassembly Potential.

These systems are assessed the same way as explained in chapter 4.2.6.2. Instead of only considering systems with a disassembly potential of DPα ≥ 0,6, all connections that should be disassembled to extract the system are taken into account. This includes systems with a low disassembly potential (Table 33) and gives a better representation of the disassembly potential of the building than considering systems with a sufficient disassembly potential.

Table 33: Disassembly potential of reusable systems

Reusable system ID	Reusable system description	System ID	Disassembly potential
1	Exterior window sill	S1	0,76
-	Brick wall	S2	**0,57**
2	Timber frame construction	S3	
2	Timber frame construction	S4	0,66
3	Interior window sill	S5	0,61
-	Mounting frame	S6	**0,54**
4	Window turn-only	S7	**0,49**
4	Window turn-only	S8	0,76
4	Window turn-only	S9	0,84

When reusable systems are composed of other products that can be disassembled, the systems are reusable on different building levels. (Table 33, timber frame construction and window turn-only).

Reusability is the goal of disassembly, therefore it is recommended to manually consider which building systems or products are reusable and calculate the SCI according to this categorization.

A project can be disassembled on different levels. When disassembly is possible on the level of which a system or product is reusable, it is considered a circular product. When a product or system can be disassembled even further, it is even better because it can be reused as a whole or in parts, increasing the options for material reutilization strategies. By assessing the building levels of each product in the BOM, a statement can be made for the level of disassembly (and possibly reusability) potential.

4.2.7. New Building Circularity Indicator (BCI)

The BCI can be calculated with the following method:

$$BCI = \frac{1}{N_b} \cdot \sum_{j=1}^{n} PCI_p \cdot N_p + \sum_{j=1}^{n} SCI_s \cdot N_s$$

In which:

BCI = Building Circularity Indicator
N_b = Sum of the Normalizing Factor of all products p and systems s
SCI_s = System Circularity Indicator of systems s
PCI_p = Product Circularity indicator of product p for $DP_p \geq 0{,}6$
N_s = Normalizing Factor (Weight, Volume, Price, etc.) of system s
N_p = Normalizing Factor (Weight, Volume, Price, etc.) of product p

The sum of the normalizing factor of all products p and systems s can be calculated with the following method:

$$N_b = \sum_{j=1}^{n} N_s + \sum_{j=1}^{n} N_p$$

Every step in the Building Circularity Indicator represents an aggregation of the previous step and adds information to that. The Building Circularity Indicator is one index number by normalizing the results with a normalizing factor like weight, volume, price, etc. Essentially the BCI consists of an aggregation of PCI_p's and SCI_s's. The PCI represents individual products and the SCI represents clusters of products.

Based on the expert opinions it is concluded that layers with a shorter lifecycle are more important than layers with a longer lifecycle and corrected the BCI according to the lifecycles of the layers of Brand. (Verberne, 2016) Because the method to categorize products in the SCI step is changed, products in a system can be part of multiple layers of Brand. This makes the relative importance of shearling layers not applicable anymore and the decision is made to drop this from the calculation. It is already discussed in the original BCI model that the sensitivity of the fuzzy variables for relative importance are disputable and that principals can make the decision not the use them. (Verberne, 2016) Without the relative importance the transparency is increased because it is not artificially decreased with the relative importance.

4.3. Validation of the new BCI assessment model

BILT is a company established in Utrecht that unites design, sustainability and circularity in an innovative residential building concept. It developed a system to put circular building in practice by developing customized method of building which are suitable to enable the circular feedback loops. (BILT, 2018) They put this into practice by developing and building a house with their system in Utrecht which temporarily functioned as their office and are now developing a residential project for Labland in Gent. This project is used as case study for the model. Data to calculate the BCI with the new assessment model is provided by BILT.

The BOM of the case study is limited to the wall panels and the floor panels. Volumes of the other products are derived from the floor plans and the rest of the input data to calculate the MCI of the products are based on assumptions. Because the majority of the volume is determined by the wall and floor panels. This does not impact the data by a lot but a more realistic scenario can be shown by complementing the data with the real scores.

The detail drawings are designed for this research and validated to be accurate by BILT. The floor plans are included in appendix 8 and the detail drawings are included in appendix 11 and 12.

Figure 43: Design of the housing project in Gent which is used as case study. Developed by BILT (BILT, 2018)

Two situations are tested with the case study.

- The entire building on building level 4. (Appendix 9, Appendix 11)
- One assembly on building level 5 & 6. (Appendix 10, Appendix 12)

Only one assembly is assessed on building level 5 & 6 because only the data for the wall and floor panels are available on that level. Furthermore, only the method to determine systems needs to be validated. This is achieved by assessing one assembly.

The same two situations are assessed with the old BCI assessment model which serves as a base-line model for the results. These results are compared with the results of the new BCI assessment model.

Volumes are used as weight and normalizing factor throughout the calculations because this is adopted by Alba Concepts and used to assess all the projects in their portfolio.

The validation is described step by step in the following paragraphs.

4.3.1. Validation of the MCI on building level 4

It is possible to apply the six-digit NL/SfB (BNA, 2005) coding system to the prefabricated components which scales them on building level 4, "product".

Table 34: Building levels of the products

ID	NL-SfB Code	Product description	**Building level**
21.0300.2760	21.23.18	BILT_wandpaneel	**4: Product level**
23.0300.2400.1	23.21.10	BILT_vloerpanel_BG	**4: Product level**
23.0300.2400.2	23.21.10	BILT_vloerpanel_1e	**4: Product level**
23.0300.2400.3	23.21.10	BILT_vloerpanel_dak	**4: Product level**
31.2.1200.2760	31.25.22	BILT_Kozijnpaneel_1200mm	**4: Product level**
22.1200.2600	22.13.31	BILT_Binnenwand_1200mm	**4: Product level**
32.31.21	32.31.21	BILT_Binnendeur	**4: Product level**
43.12.10	43.12.10	BILT_Verhoogdvloersysteem300x300	**4: Product level**
41.12.41	41.12.41	BILT_Buitenwandbekleding	**4: Product level**

The ground floor, first floor and roof panels are identical. Because the detail drawings are different from each other these are split.

The input to calculate the MCI for these products are included in Appendix 9. The results are shown in Table 39.

Table 35: MCI of products on building level 4

ID	NL-SfB Code	Product description	**MCIp**
21.0300.2760	21.23.18	BILT_wandpaneel	**0.80**
23.0300.2400.1	23.21.10	BILT_vloerpanel_BG	**0.81**
23.0300.2400.2	23.21.10	BILT_vloerpanel_1e	**0.81**
23.0300.2400.3	23.21.10	BILT_vloerpanel_dak	**0.81**
31.2.1200.2760	31.25.22	BILT_Kozijnpaneel_1200mm	**0.59**
22.1200.2600	22.13.31	BILT_Binnenwand_1200mm	**0.40**
32.31.21	32.31.21	BILT_Binnendeur	**0.59**
43.12.10	43.12.10	BILT_VerhoogdVloersysteem300x300	**0.86**
41.12.41	41.12.41	BILT_Buitenwandbekleding	**0.63**

4.3.2. Validation of the PCI on building level 4

By assessing the detail drawings included in Appendix 11 the following results are derived.

Table 36: Disassembly potential of the products on building level 4

ID	Description	Assembly shape	Independency	Method of Fabrication	Type of Relational Pattern	**Product Disassembly potential (PDp)**	Accessibility to connection	Type of connection	Assembly Sequence	**Connection Disassembly potential (CDp)**	**Disassembly potential DPp**
21.0300.2760	BILT_wandpaneel	1.00	0.10	1.00	1.00	**3.10**	0.80	0.80	1.00	**2.60**	**0.81**
23.0300.2400.1	BILT_vloerpanel _BG	0.10	0.10	1.00	0.60	**1.80**	0.80	0.80	1.00	**2.60**	**0.63**
23.0300.2400.2	BILT_vloerpanel _1e	0.10	0.10	1.00	1.00	**2.20**	1.00	0.80	1.00	**2.80**	**0.71**
23.0300.2400.3	BILT_vloerpanel _dak	1.00	0.10	1.00	1.00	**3.10**	1.00	0.80	1.00	**2.80**	**0.84**
31.2.1200.2760	BILT_Kozijnpaneel _1200mm	1.00	1.00	1.00	1.00	**4.00**	1.00	0.80	1.00	**2.80**	**0.97**

22.1200.2600	BILT_Binnenwand _1200mm	1.00	0.40	0.50	1.00	**2.90**	0.60	0.10	1.00	**1.70**	**0.66**
32.31.21	BILT_Binnendeur	1.00	1.00	1.00	1.00	**4.00**	1.00	1.00	0.50	**2.50**	**0.93**
43.12.10	BILT_Verhoogd Vloersysteem 300x300	1.00	1.00	1.00	1.00	**4.00**	0.80	1.00	1.00	**2.80**	**0.97**
41.12.41	BILT_Buitenwand bekleding	0.40	0.40	1.00	1.00	**2.80**	0.80	0.80	1.00	**2.60**	**0.77**

All the products have a Disassembly potential ≥ 0,6 which is determined as the threshold for disassembly possibility. Overall the floor panel on the ground floor and the interior wall have a lower disassembly potential. For the floor panel this is mainly the influence of the Product Disassembly Factors. For the interior wall it is a combination of Product Disassembly factors and Connection Disassembly factors.

Based on the MCI and the DP the PCI of all problems are calculated in Table 37.

Table 37: Product Circularity Indicator of all products on building level 4

ID	NL-SfB Code	Product description	MCIp	DPp	PCIp
21.0300.2760	21.23.18	BILT_wandpaneel	**0.80**	**0.81**	**0.64**
23.0300.2400.1	23.21.10	BILT_vloerpanel_BG	**0.81**	**0.63**	**0.50**
23.0300.2400.2	23.21.10	BILT_vloerpanel_1e	**0.81**	**0.71**	**0.57**
23.0300.2400.3	23.21.10	BILT_vloerpanel_dak	**0.81**	**0.84**	**0.67**
31.2.1200.2760	31.25.22	BILT_Kozijnpaneel_1200mm	**0.59**	**0.97**	**0.57**
22.1200.2600	22.13.31	BILT_Binnenwand_1200mm	**0.40**	**0.66**	**0.26**
32.31.21	32.31.21	BILT_Binnendeur	**0.59**	**0.93**	**0.55**
43.12.10	43.12.10	BILT_VerhoogdVloersysteem300x300	**0.86**	**0.97**	**0.83**
41.12.41	41.12.41	BILT_Buitenwandbekleding	**0.63**	**0.77**	**0.49**

4.3.3. Validation of the SCI on building level 4

The systems are determined from the disassembly potential of the product. The Products defined on building level 4 all have a disassembly potential of ≥ 0,6. Furthermore, they are developed to be reused on this building level. This means that this step in the Building Circularity Indicator assessment model is not necessary. The Building Circularity Indicator is calculated with the following method:

$$BCI = \frac{1}{N_b} \cdot \sum_{j=1}^{n} SCI_s \cdot N_s + \sum_{j=1}^{n} PCI_p \cdot N_p$$

In which:

PCI_p = Product Circularity indicator of product p for $DP_p \geq 0{,}6$

Therefore SCI_s= 0 and the Building Circularity Indicator in this case is:

$$BCI = \sum_{j=1}^{n} PCI_p \cdot V_p$$

4.3.4. Validation of the SCI on building level 4

The BCI is an aggregation of the PCI's normalized by total volume. The SCI step is not necessary because all products have a higher disassembly potential than the threshold, and all products are developed to be reused on this building level. The BCI can be calculated with the data in Table 38.

Table 38: Input to assess the BCI score of the project on building level 4.

ID	NL-SfB Code	Product description	**N_p**	**PCI_p**
21.0300.2760	21.23.18	BILT_wandpaneel	43.75	0.65
23.0300.2400.1	23.21.10	BILT_vloerpanel_BG	60.05	0.51
23.0300.2400.2	23.21.10	BILT_vloerpanel_1e	60.05	0.58
23.0300.2400.3	23.21.10	BILT_vloerpanel_dak	60.05	0.68
31.2.1200.2760	31.25.22	BILT_Kozijnpaneel_1200mm	2.00	0.57
22.1200.2600	22.13.31	BILT_Binnenwand_1200mm	5.00	0.26
32.31.21	32.31.21	BILT_Binnendeur	0.30	0.55
43.12.10	43.12.10	BILT_VerhoogdVloersysteem300x300	8.00	0.84
41.12.41	41.12.41	BILT_Buitenwandbekleding	7.00	0.49
Total			**246,20**	

.

$$BCI = \sum_{j=1}^{n} PCI_p \cdot V_p = \frac{1}{246.20} \cdot 147.52 = 0.60$$

4.3.5. Validation of the MCI on building level 5 & 6

The following assembly and detail drawing is selected to assess to validate the method of determining systems. The results do not reflect the entire building, only this assembly.

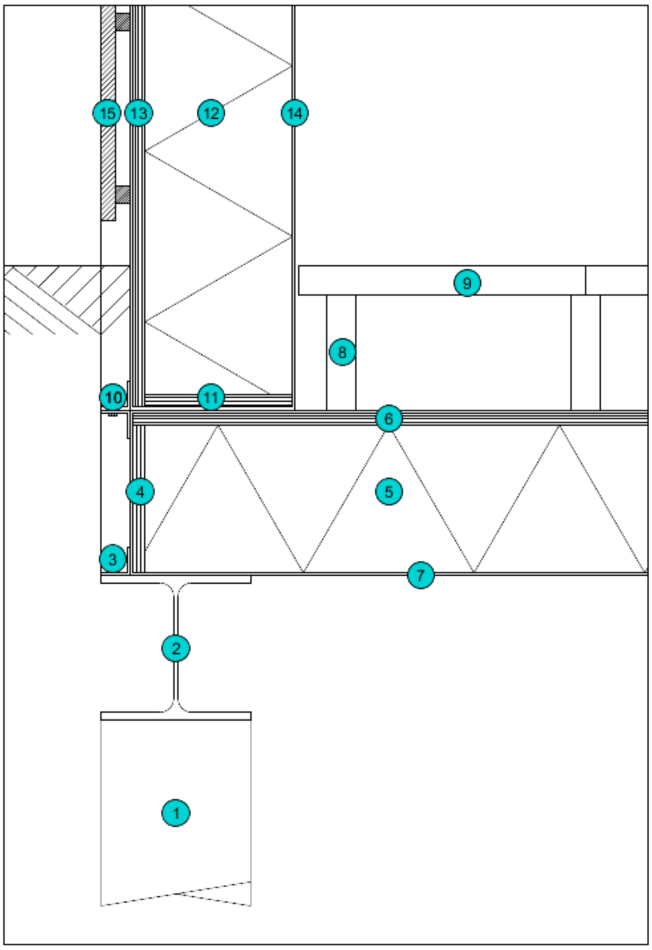


Figure 44: Detail drawing of BILT system

First the building levels of these products are categorized.

Table 39: Building levels of the products

ID	NL-SfB Code	Product description	**Building level**
21.0300.2760	21.23.18	BILT_wandpaneel	**4: Product level**
21.0300.2760.1	X	Aluminium schil	**6: Material level**
21.0300.2760.2	X	Multiplex schil	**6: Material level**
21.0300.2760.3	X	Multiplex tussenschotten	**5: Component level**
21.0300.2760.4	X	Everuse	**5: Component level**
21.0300.2760.5	X	Extrusieprofiel	**6: Material level**
43.1.1	X	Vloerpaneel	**5: Component level**
43.1.2	X	Stelpootjes	**5: Component level**
41.1	41.12.41	BILT_Buitenwandbekleding	**4: Product level**
16.1	16.12	Funderingsbalk	**3: Element level**

The majority of the products are determined on building level 5 & 6. Some of them are a higher level but this does not influence the rest of the calculation.

The input to calculate the MCI for these products are included in Appendix 10. A part of the calculation is displayed in Table 40 and 37.

Table 40: Input, output and lifecycle data of the wall panel

Product description	Volume (m^3)	Materials					
		Input		Output			
		Virgin %	Reused %	Landfill / energy recovery (%)	Reuse %	Product lifecycle	Systematic lifecycle
BILT_wandpaneel	**43,75**			**0%**	**100%**	**100**	**100**
Aluminium schil	0,20	40%	60%	0%	100%	100	100
Multiplex schil	7,46	100%	0%	0%	100%	100	100
Multiplex tussenschotten	1,96	100%	0%	0%	100%	100	100
Everuse	33,91	0%	100%	0%	100%	100	100
Extrusie profiel	0,21	20%	80%	0%	100%	100	100

Table 41: Material Circularity Indicator calculation model for the wall panel

Product description	Material Circularity Indicator calculation model					
	V	W	X	LFI	Fx	**MCI**
BILT_wandpaneel	**9,51**	**-**	**1**	**0,11**	**0,9**	**0.80**
Aluminium schil	0,04	-	1	0,10	0,9	0.72
Multiplex schil	7,46	-	1	0,50	0,9	0.45
Multiplex tussenschotten	1,96	-	1	0,50	0,9	0.45
Everuse	-	-	1	-	0,9	1.00
Extrusie profiel	0,04	-	1	0,10	0,9	0.81

4.3.6. Validation of the PCI on building level 5 & 6

To validate the model of combining products into systems and whether the products can be disassembled on a lower level, one assembly is tested on this level. The full calculation model is included in Appendix 10. The detail drawing and the relational pattern are shown in Figure 45.

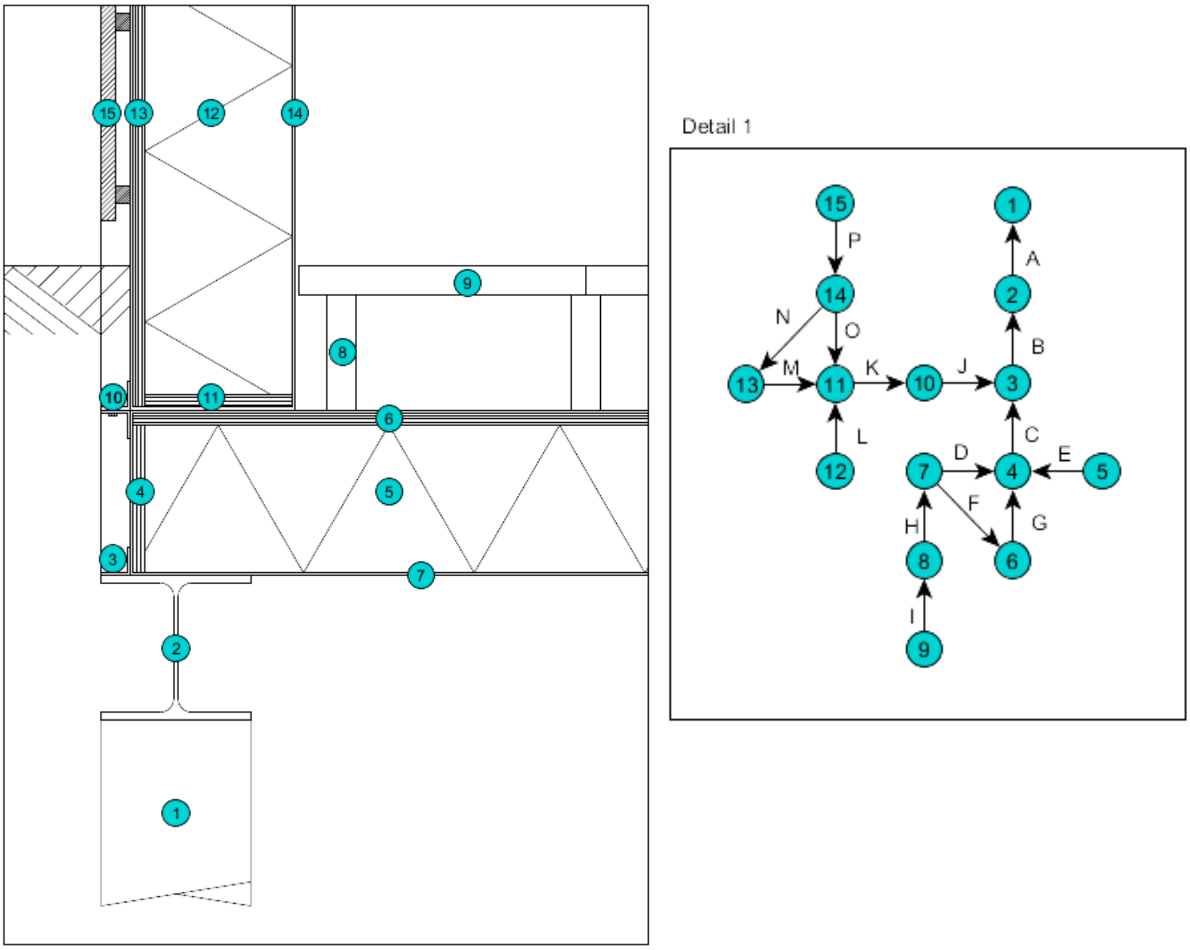


Figure 45: Detail drawing of BILT (BILT, 2018) and relational pattern of one assembly on building level 5 & 6

The following results are derived from calculating the Disassembly Potential of this assembly.

Table 42: Disassembly potential of the products of BILT on building level 5 & 6 (BILT, 2018)

ID	Description	Assembly shape	Independency	Method of Fabrication	Type of Relational Pattern	Product Disassembly potential (PDp)	Accessibility to connection	Type of connection	Assembly Sequence	Connection Disassembly potential (CDp)	Disassembly potential DPp
16.1	Funderingsbalk	1,00	1,00	1,00	1,00	**4,00**	0,80	0,80	0,50	**2,10**	**0,87**
23.1.5	Extrusieprofiel	1,00	0,80	1,00	1,00	**3,80**	0,80	0,80	1,00	**2,60**	**0,91**
23.1.3	Multiplex tussenschotten	0,10	0,10	1,00	0,40	**1,60**	0,40	0,20	1,00	**1,60**	**0,46**
23.1.4	Everuse	0,10	0,10	1,00	1,00	**2,20**	0,10	1,00	0,10	**1,20**	**0,49**
23.1.2	Multiplex schil	0,10	0,10	1,00	0,60	**1,80**	0,10	0,20	1,00	**1,30**	**0,44**
23.1.1	Aluminium schil	0,10	0,10	1,00	1,00	**2,20**	0,10	0,10	1,00	**1,20**	**0,49**
43.1.2	Stelpootjes	1,00	1,00	1,00	1,00	**4,00**	0,80	1,00	0,10	**1,90**	**0,84**
43.1.1	Vloerpaneel	1,00	1,00	1,00	1,00	**4,00**	0,80	1,00	1,00	**2,80**	**0,97**
21.1.5	Extrusieprofiel	1,00	0,80	1,00	1,00	**3,80**	1,00	0,80	1,00	**2,80**	**0,94**
21.1.3	Multiplex tussenschotten	0,10	0,10	1,00	0,40	**1,60**	0,40	0,20	1,00	**1,60**	**0,46**
21.1.4	Everuse	0,10	0,10	1,00	1,00	**2,20**	0,10	1,00	0,10	**1,20**	**0,49**
21.1.2	Multiplex schil	0,10	0,10	1,00	1,00	**2,20**	0,10	0,20	1,00	**1,30**	**0,50**
21.1.1	Aluminium schil	0,70	0,10	1,00	1,00	**2,80**	0,10	0,10	1,00	**1,20**	**0,57**
41.1	BILT_Buitenwand bekleding	0,40	1,00	0,50	1,00	**2,90**	0,80	0,80	0,80	**1,70**	**0,66**

The following results are derived from calculating the Disassembly Potential of this assembly.

Table 42 shows that the disassembly potential does not score as high compared to the assessment on building level 4 (Table 36). This is expected because the product are designed to be disassembled and reused on that level. The expectation is that by determining systems with the disassembly potential as criteria, the resulting systems are identical to the products on building level 4.

4.3.7. Validation of the SCI on building level 5 & 6

On building level 5 & 6 there are multiple products that have a Disassembly potential ≤ 0,6. These products are grouped into systems. (Figure 46)

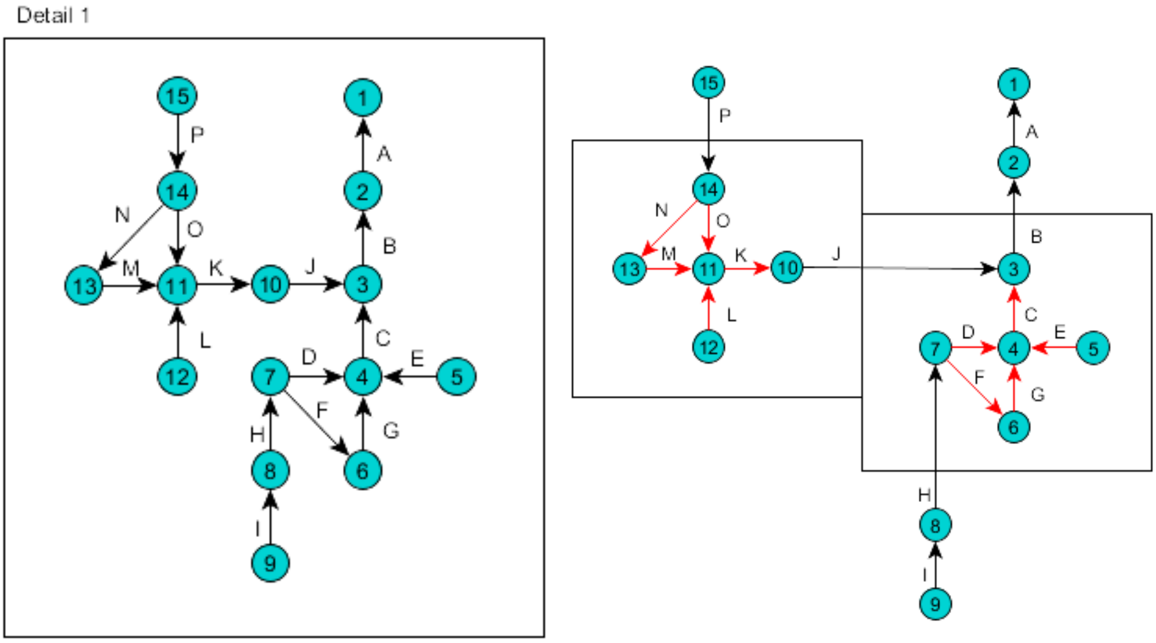


Figure 46: The relational pattern of the assembly of BILT (BILT, 2018) is transformed to systems with a disassembly potential of ≥ 0,6.

The next step would be to assess the reusability of the systems and remove any product that impede the reusability of it and include in the assessment individually. However, the defined systems are also designed to be reusable so this step is unnecessary.

The system disassembly potential can be assessed with the same method as the product disassembly potential. Because the defined systems are identical to the products on building level 4, the disassembly potential is also the same. (Table 43)

Table 43: Products and systems defined on building level 5 & 6

ID	Node ID	Product description	Product level	Disassembly potential DP_s
Product 1				0.87
16.1	2	Funderingsbalk	Element level	
System 1		BILT_vloerpanel_BG		0.63
23.1.5	3	Extrusieprofiel	Material level	
23.1.3	4	Multiplex tussenschotten	Material level	
23.1.4	5	Everuse	Component level	
23.1.2	6	Multiplex schil	Material level	
23.1.1	7	Aluminium schil	Material level	
Product 2				0.84
43.1.2	8	Stelpootjes	Component level	
Product 3				0.97
43.1.1	9	Vloerpaneel	Component level	
System2		BILT_vloerpanel_BG		0.81
21.1.5	10	Extrusieprofiel	Material level	
21.1.3	11	Multiplex tussenschotten	Material level	
21.1.4	12	Everuse	Component level	
21.1.2	13	Multiplex schil	Material level	
21.1.1	14	Aluminium schil	Material level	
Product 4				0.66
41.1	15	BILT_Buitenwandbekleding	Product level	

4.3.8. Validation of the BCI on building level 5 & 6

To calculate an accurate BCI the entire building has to be assessed on this level. Only one assembly is regarded in this validation step. The BCI therefore reflects the circularity indicator of that assembly.

Table 44: BCI on building level 5 & 6 based on one assembly

ID	Product description	N_p	PCI_p
Product 1	Funderingsbalk	4.00	0.39
System 1	BILT_vloerpanel_BG	43.75	0.66
Product 2	Stelpootjes	1.00	0.72
Product 3	Vloerpaneel	8.00	0.42
System 2	BILT_vloerpanel_BG	60.05	0.50
Product 4	BILT_Buitenwandbekleding	7.00	0.41
Total		**123.80**	

$$BCI = \frac{1}{N_b} \cdot \sum_{j=1}^{n} PCI_p \cdot N_p + \sum_{j=1}^{n} SCI_s \cdot N_s = \frac{1}{123.80} \cdot (8.53 + 59.05) = 0.55$$

4.3.9. Comparing the new BCI with the old BCI

The BCI of the case study is calculated on both building levels with the new BCI assessment model and the old BCI assessment model. In appendix 11 these calculations are included. The results are shown in Table 45.

Table 45: Comparing the BCI Score of the old and new BCI assessment model

	BCI score		
Building level	Old BCI	New BCI	Difference
Building level 4	0.57	0.6	0.03
Building level 5 & 6	0.48	0.55	0.07

There is no framework to assess the disassembly factors in the old BCI assessment model. Because five out of seven disassembly factors are the same, the framework developed in this research is used for this.

The difference between results is relatively low on building level 4 and is bigger on lower building levels due to new categorization of systems. Building level 5 & 6 only consists of one assembly. It is expected that the differences will become bigger by expanding this with more assemblies.

4.4. Discussion of the new BCI assessment model

Limitations are identified in the BCI assessment model regarding the assessment of disassembly. This research aimed to solve most of these limitations by redeveloping the calculation method of disassembly potential in the BCI assessment model.

New and existing factors that influence disassembly in the entire building development process are adopted in the model based on the importance of the factors determined in chapter 0. In total twelve factors where adopted of which seven are included in the calculation to assess the BCI.

The BCI assessment model is developed to calculate technical requirements. Not all identified factors are technical of nature but also process-based and financial-based. These are incorporated in the BCI assessment model as preconditions and drivers for disassembly which should be incorporated in the building development process to enable disassembly.

The BCI is a theoretical indicator of the circular potential of a building. It is always important to interpret the results and reflect back to the practical implications.

4.4.1. Discussion of the Material Circularity Indicator (MCI)

The Material Circularity Indicator calculates the KPI for material properties and in this step disassembly is not prevalent yet. Therefore no changes are made in the MCI step of the calculation model. The only addition is categorizing the products according to building levels in the Bill of Materials (BOM) which enables a more transparent comparison between products throughout the calculation steps and on which level the products can be disassembled. The level of input determines the calculation of the BCI. The building levels can also serve as guideline for actors to determine a requirement for the level of input of the BOM. This is not required to be able to calculate the BCI.

The assessment of building levels is always subject to a situational context. To make this more objective, categorizing with a combination of the NL/SfB (BNA, 2005) and the STABU2 method (STABU, 2015) is proposed. This works until building level 4 (product) which is defined by the six-digit numbers of the NL/SfB. Building levels 5 and 6 are assessed with the STABU2 method. Because the STABU2 method is not open source and also works with a different classification system, it is not an ideal method. An eight-digit NL/SfB or any other comprehensive classification system that incorporates the lower levels is recommended to be adopted when it is developed.

4.4.2. Discussion of the Product Circularity Indicator (PCI)

The PCI and the SCI are calculated with the MCI and the new Disassembly Potential assessment method. The technical factors remain based on the fuzzy variables (Durmisevic, 2006) like the original calculation model. Some changes have been made to the factors type of connection, assembly sequence and relational pattern based on assumptions to make them applicable. These assumptions have to be validated.

The fuzzy variables define several categories and this includes the uncertain nature of assessing disassembly potential. This also results in a degree of subjectivity in the assessment of each factor. With the new method of assessing relational patterns this is more transparent because the framework for the assessment is clearly defined.

An attempt is done to weight the factors for relative importance to incorporate in the model. Because no significant differences between the importance of the factors is found in chapter 0. In practice this does lead to some debatable results. For instance using a dry connection has the same impact as assembling products together with the same building level. The results of chapter 3 and the results of different scenarios with the new disassembly potential assessment model can be used for follow-up research to determining the relative importance between disassembly factors.

The factors included in the model are not tested for independency and relations between factors may exist. These relations are not considered and adding relations between disassembly factors, products and systems would be the optimal result of modeling disassembly potential.

Relational patterns are used as a method to assess disassembly which functions as a framework to relate back to during and after the assessment of the disassembly potential. The detail drawing is chosen to base the relational pattern on. Another method to determine the relational pattern is by using a Building Information Model (BIM). This contains precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities required to realize the building (Eastman, Teicholz, Sacks, & Liston, 2008). BIM has the potential to be usable to assess disassembly potential. After doing an explorative review no research can be found to accurately represent connections in BIM that is usable to do this. Therefore this research sticks with the detail drawings. BIM has potential to simplify and automate the assessment method when it can recognize which products are connected with each other. Research towards how to implement a BIM based assessment method in the BCI is recommended.

Developing a BIM tool will certainly help in reducing the time required to set up relational patterns and making the relational patterns more comprehensive by including the entire building instead of only the most important detail drawings.

4.4.3. Discussion of the System Circularity Indicator (SCI)

The System Circularity Indicator is changed entirely in the new BCI assessment model. Originally the products were grouped per system layer of Brand and the mass of the products in the systems were used as normalizing factor.

Two options are given to categorize products in systems:

- Using a Disassembly Potential threshold to group products in a system.
- Using reusability potential to group products in a system.

The Disassembly Potential threshold α is set at 0.6. Because the disassembly potential ranges between zero and one, this is still a high score and which is the result of some factors having a relatively high impact. Adding more case studies by applying the method in practice will also show how this threshold holds up in practice. It is important to always relate the score back to the practical implications to understand whether the threshold still reflects the reality.

Grouping the systems according to disassembly potential can give a skewed result because all the systems will have a high disassembly potential and this will influence the final BCI score. Therefore it is recommended to group the systems to reusability. Material reutilization is mentioned multiple times in this research and is an important aspect of enabling the circular economy. When a system can be disassembled, but not reused in that way due to other reasons, the system is essentially useless. Therefore reusability should be on the top of the mind when using the disassembly potential assessment method in the BCI.

The case study defines systems and products that are reusable, which is the expected result because it is designed to be disassembled. By making disassembly possible on lower building levels, even more circular loops can be enabled. Because disassembly in building development is already difficult to realize, it would hold back developments in the building industry when disassembly on a higher level is penalized compared to lower levels. Instead all products are categorized according to their building level at the start of the assessment which results in the ability to indicate on which level a product can be disassembled.

4.4.4. Discussion of the Building Circularity Indicator (BCI)

The BCI gives a representation about how well the total building performs regarding circular ambitions. It can be used to compare different building with each other. The most information is however embedded in the PCI's and the SCI's. With these results it is possible to understand which parts of a building underperform regarding the circular ambition in a project. Therefore the BCI is not only a measurement tool, it is also a guiding tool to achieve better results and to enable a more circular economy in the building industry.

Not all data to calculate the BCI of the case study is available, therefore some assumptions are made. The wall and floor panels are however accurate and these make up about 91% of the total volume of the building, which is very determinant in the BCI score. Complimenting the available data will give an even more realistic result.

After the case study is conducted, the method and the results are thoroughly discussed with BILT. In reality the results reflect the experience of BILT for assembling and disassembling their model house that is located in Utrecht. The only remarks are that in practice the window frames are slightly less easy to disassemble so this score should be somewhat lower in comparison to other products. The differences between the floor panels on different floor levels also reflect their experience that they are more difficult to disassemble.

The BCI of the case study is calculated with both the old and the new method. This resulted in slight differences between the results for both validations when considering two different building levels, 0.03 and 0.07 for the higher and lower building level respectively. Only one assembly is tested on a lower building level and the expectation is that the difference will increase when more assemblies are added.

A limitation identified for the old BCI assessment model is that there is no framework to assess disassembly. This makes it difficult to make a comprehensive assessment for the disassembly factors in the old model. Therefore it has to be noted that the framework developed in this research is used to calculate the old BCI. Even when the end results do not seem to differ that much, the new framework is an important result of this research.

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5

Conclusion of the research

This research sets out to answer the research question;

How can the Building Circularity Indicator assessment model be adjusted to incorporate an integral method for assessing building disassembly potential?

A conceptual model is built to incorporate the assessment of building disassembly integrally in the BCI assessment model. This is based on the identified limitations, the selected factors for building disassembly and their weights. The model is validated for face validity with a case study and the results are compared with the old BCI assessment model.

In this chapter the research question and sub-questions are answered. Followed up by a reflection on the societal and scientific relevance. Several findings are considered out of the scope of this research but are interesting for follow-up research. These are described in the recommendations.

5.1. Answers to the Research questions

First the main research question of this research is answered. This research question is answered by answering all the research sub-questions throughout this research and incorporating the results. The answer to the research question is the overall conclusion of this research. After this is done, the answers of all research sub-questions are displayed.

The main research question of this research is:

How can the disassembly potential of a building be assessed as an integral part of building circularity and what influence does this have on the Building Circularity Indicator assessment model?

The Building Circularity Indicator assessment model is used as framework of for this research. Calculating the disassembly potential of products in a building determines fifty percent of the circular potential of a building. In this research, limitations of the BCI assessment model are identified. By developing a new method to assess the building disassembly potential in the BCI assessment model, disassembly is assessed as an integral part of building circularity. The following changes are made:

- The building level of all materials and products in the BOM are determined. A classification method to do this is proposed in this research based on existing methods.
- Detail drawings are used to develop relational patterns which serve as framework to assess the disassembly potential. A distinction is made between technical factors that asses the product disassembly potential and the connection disassembly potential.
- Twelve most important of the twenty-five disassembly factors are incorporated in the model based on testing the importance of factors with experts in the field and comparing the results with existing research
- By incorporating process-based factors as preconditions and financial based factors as drivers. These can be used to consider disassembly in the building development process.
- No significant difference between the results of weighted disassembly factors and the baseline model (equal weight) is found. Therefore the decision is made to use equal weights for disassembly factors in the BCI assessment model.
- The Disassembly potential of products (PCI) and systems (SCI) are assessed. Products can be part of systems and vice versa. The relations between different products, different systems and between products and systems are incorporated in the model. This integrates a system way of thinking.
- By grouping products into reusable systems and determining the disassembly potential of these, the goal of material reutilization is actively integrated in the model. Another option to use a disassembly threshold is given.

The influence of these changes is that the PCI, SCI and BCI steps are changed. Additions are made in the MCI step and in the preconditions and drivers.

With the resulting model it is possible to determine on which building level products, systems and the entire building can be disassembled. This makes comparing results with each other possible.

Furthermore a framework for assessing the disassembly potential is incorporated by using relational patterns. This makes the calculation comprehensive for each product and connection. Because the assessment is based on the relational pattern which in turn is based on a detail drawing, it is always possible to relate decisions back to something.

Material reutilization as a goal for disassembly possibilities is a voluntary but recommended part of the calculation to determine systems. Not only this incorporates a system way of thinking but this also incorporates the material reutilization directly in the model which makes disassembly assessment an integral part for building circularity.

The exact influence of the calculation method on the score cannot be determined with a limited amount of case studies but the influence seems to be higher on lower building levels than on higher building levels. The BCI score is 0.03 higher on building level 4 with the new BCI assessment model and 0.07 higher on building level 5 & 6.

The sub-questions of this research are:

Why is building disassembly important to enable the circular economy?

The circular economy consists of three aspects. The ecological cycle, the economy model and the technological cycle. The goal of the technological cycle is to iterate (building) materials through the economy with different feedback loops. Short loops (maintain or reuse) are preferred over long loops (Recycling). Because buildings are nowadays complex entities of interconnected materials, the ability to disassemble materials plays and important role in enabling material reutilization and thus the circular economy. Three principles to guide the circular economy are:

- Design out of waste; this is achieved by Design for Disassembly, among other design principles.
- Build resilience through diversity; Disassembly enabled adaptivity of buildings by making parts replaceable.
- Think in systems; Understanding relationships between products and systems helps to make disassembly possible.

The Building Circularity Indicator assessment model is a measurement tool for circular buildings that incorporates disassembly as a KPI for circular buildings. This determines fifty percent of the score.

Which factors influence disassembly potential of buildings in the entire building development process?

Design for Disassembly is used a as a baseline to identify which factors influence whether a building is disassembled at the end of the lifecycle. DfD is a design principle but a deconstruction process requires changes to the progress of construction methods, process and planning. (Rios et al., 2015). This research considers the entire building development process to identify factors that enable building disassembly. Twenty-five disassembly factors influence the disassembly potential of buildings which are categorized as Technical, Process-based and Financial-based factors according to the IPF-model. (van Oppen, 2017)

Table 46: Factors that influence disassembly categorized as technical, process-based and financial-based factors.

Technical disassembly factors	Process-based disassembly factors	Financial-based disassembly factors
Functional separation	Coding and marking	Disassembly costs
Independency	Disassembly instructions	Disassembly time
Structure of material levels	User participation	
Type of base element	Disassembler expertise	
Technical/use life cycle coordination	Number of operations	
Ease of handling	Deconstruction safety	
Type of relational pattern		
Assembly direction based on assembly type		
Assembly sequence		
Assembly shape		
Method of fabrication		
Type of connection		
Accessibility to connection		
Tolerance between components		
Amount of fasteners		
Hazardousness of materials		
Required tools		

Which disassembly factors have to be included in the new BCI assessment model to determine the disassembly potential of a building?

Including all twenty-five identified disassembly factors in the BCI assessment model to determine the disassembly potential of a building would make it too complex. Based on a survey the most important factors are identified. These are compared with the Transformation Capacity factors (Durmisevic, 2006), the IPF-model (van Oppen, 2017) and the existing BCI factors (Verberne, 2016). Twelve disassembly factors are selected to be included in the new BCI assessment model to determine the disassembly potential of a building.

Table 47: Selection of disassembly factors to include in the BCI assessment model

Technical disassembly factors	Process-based disassembly factors	Financial-based disassembly factors
Independency	Disassembly instructions	Disassembly costs
Type of relational pattern	Disassembler expertise	
Assembly sequence	Number of operations	
Assembly shape	Deconstruction safety	
Method of fabrication		
Type of connection		
Accessibility to connection		

What is the relative importance (weight) of the disassembly factors that can be implemented in the new BCI assessment model?

The hypothesis is stated that there is a difference between the importance of disassembly factors. This research aimed to determine these relative weights Different weights are determined with a survey, which are validated in the new BCI assessment model to compare the results with the baseline model (equal weights). The difference between weighted disassembly factors and the baseline model is insignificant. Therefore the decision is made to implement equal weights for the disassembly factors in the new BCI assessment model. The hypothesis cannot be accepted based on the results of this research.

How can the decomposition of building levels be used to determine on which level the building can be disassembled?

A Bill of Materials (BOM) is used as input to calculate the MCI. This input is categorized according to the determined building levels. A combination of the NL/SfB (BNA, 2005) and the STABU2 (STABU, 2015) method is proposed for this. Determining the building levels dictate on which level the building can be disassembled. This has no influence on the calculation method but it enables actors to compare the disassembly potential of products with each other more objectively or gives actors the possibility to require a certain level of input for the BOM.

Which method can be used assess the disassembly potential in the Building Circularity Indicator assessment model?

Instead of using the BOM to determine the disassembly potential of a building, a relational pattern is used. This serves as a framework in the BCI assessment model. The relational pattern gives an overview of all products in an assembly and which products are connected with each other. To create a relational pattern, detail drawings are used. The building development team determines the most important detail drawings to include in the BCI assessment model. By assigning unique codes to every material in the BOM and the detail drawings, a Bill of Disassembly Potential is made. To do this, a distinction between Product Disassembly Potential (PD) and Connection Disassembly Potential (CD) is made, together this determines the Disassembly Potential (DP) of a product or a system. This makes the assessment of disassembly potential of a building in the BCI assessment model more transparent. It is tied to the relational pattern which is tied to the detail drawing.

How can the assessment of building disassembly potential be integrally incorporated in the BCI assessment model?

The categorization of products and materials for building levels in the MCI step is used to determine on which building level the products can be disassembled. The Disassembly Potential of each product is calculated in the PCI step. A choice is made to either categorize products into systems in the SCI step according to the reusability of the systems or to categorize products according to the Disassembly Potential threshold (DPα). The threshold is set on 0.60 based on the results of the case studies. The Disassembly Potential of all systems is assessed with the same method used in the PCI step. In the BCI step the individual products and the determined systems in the SCI step are aggregated into one indicator the building circularity. Disassembly potential is therefore integrally part of each step of the BCI assessment model. Additionally, preconditions and drivers for disassembly are incorporated in the BCI assessment model. These do not influence the score but they are viewed as important factors to enable disassembly. Preconditions and drivers can be used by actors in the building development process to guide the process to enable disassembly. Other methods can be used to determine how well the preconditions and drivers are integrated in the building development process.

5.2. Relevance

This chapter first describes the scientific relevance of this research by reflecting back on the results. Followed up by a discussion how this research is relevant for society.

5.2.1. Scientific Relevance

"For the circular economy to become a success, a simple measure of achievement is necessary as a first step towards fully integrated reporting." (Kok et al., 2013) with this among other things in mind the BCI assessment model (Verberne, 2016) is developed. It is one of the first academic models that aims to determine the circular potential of a building. It does so by expanding on the Material Circularity Indicator (Ellen MacArthur Foundation & Granta Design, 2015)

This research made a step forwards in this need for a measurement tool by improving limitations and including disassembly in the model in a more integral way. This is achieved by adding a framework for assessment, identifying additional and validating existing disassembly factors in the model and validating the model with a case study that is actually a building in development.

The technical cycle of the circular Economy is with the existing building methodologies important to make the built environment more circular. This research made the model include the technical cycle more comprehensively which is an important step to help understand the Circular Economy principle.

5.2.2. Societal Relevance

We live in a linear take-make-dispose economy. This has contributed to the ecological problems of today. It is estimated that 32.7% of the total waste generation, amounts of 31% of the total energy use (International Energy Agency, 2015) and 9% of the greenhouse gas emission (European Union, 2016). Research towards the circular economy in the built environment can help shifting away from a linear economy to reduce waste, raw material extraction from the planet and global warming. The Dutch government set a goal to be fully circular in 2050 (Ministry of infrastructure and the environment & Ministry of economic affairs, 2016) which is ambitious but this research contributes maybe even in a small way to get there.

The economic potential estimated by the Ellen MacArthur Foundation is a saving of 380-630 billion dollars, just by looking at a subset of manufacturing sectors in the European Union (Ellen MacArthur Foundation, 2013) Grasping this potential requires new business models and revenue models. Enabling disassembly of buildings is one of the factors that enables material reutilization. A measurement model may be used to guide developments that can be disassembled. This opens up new business and value cases that can be exploited

5.3. Recommendations

A literature research is conducted to identify factors that are important for disassembly of buildings. Multiple researchers relate factors with each other, implying dependencies. These relations are ignored in this research and the disassembly factors are regarded as independent factors.. Mapping the relations between disassembly factors is recommended.

No significant difference between disassembly factors is found in this research. The hypothesis is therefore not accepted however the expectation that some factors have a bigger influence than others is still present. A qualitative follow-up research to validate the results should be performed.. It is recommended to use results of case studies for this to make the practical implications understandable.

This research did not validate the influence of disassembly on the total circular potential. The original ratio of MCI times DP is maintained. First of all this makes it difficult to achieve a high circular potential even with a very high MCI and DP. Second of all it is unknown whether this ratio holds up to reality. It is recommended to validate the impact of these factors in future research.

Relational patterns are developed with detail drawings as blue print for the assembly. For complex assemblies this can be time consuming. A BIM based method can help in automatically deriving relational patterns of complete buildings which speeds up the process for assessing the disassembly potential. No such research is found and developing a tool for this is recommended.

Systems can be determined according to disassembly potential or reusability. Reusability is a recurring topic throughout this research. Disassembly is done to enable material reutilization which enables the circular economy. Identifying what makes a product or system reusable is out of the scope of this research. The next step to incorporate a reusability assessment is recommended.

Other aspects that have no effect on disassembly are mentioned in the research by Verberne (2016) Because they are out of the scope of this research, they are not mentioned before but are expected to be important subjects to expand upon with the BCI assessment model.

- Including the biological cycles,
- Downcycling/upcycling
- The utility factor.
- Multiple lifecycle assessment
- Incorporation of the BCI in a certification or a label
- How to deal with secrecy of data within the sector

Additional out-of-scope subjects identified in this research are:

- Including environmental impact in the assessment instead of volumes, mass, etc.
- Reusability factors.

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Appendices

Appendix 1: BCI assessment model calculation method

Material Circularity Indicator (MCI)
The MCI is developed form the following characteristics
- The mass V of virgin material used in manufacture.
- The mass W of unrecoverable waste that is attributed after usage (primarily).
- The Utility factor X with the lifetime/systematic value of the product.

Based on these characteristics the following quantities can be determined:
- The Linear Flow Index, which is about the input and output of materials;
- The Material Circularity Indicator (MCI_p), which is about the products' level of circularity.

The material input is calculated in the following way.

$$V(\chi) = M(\chi)(1 - NVRC(\chi)),$$

1: Fraction of feedstock from virgin sources for each sub-assembly

Where
$V(\chi)$ is the fraction of feedstock from virgin sources for each sub-assembly;
$M(\chi)$ is the total mass of the sub-assembly;
$NVRC(\chi)$is the fraction of feedstock from non-virgin sources for each sub-assembly.

The total virgin material for a product V using the summation of all different sub-assemblies, parts and/or materials is:

$$V = \Sigma V(\chi)$$

The material output is calculated in the following way.

$$W = M\ (1 - \ FRU)$$

Where
W is the amount of waste;
M is the total mass of a product;
FRU is the fraction of a product used for reuse, refurbishing, remanufacturing, and recycling.

The utility factor is determined in the following way.

$$X = \frac{Lp}{Lsys}$$

Where
Lp is the length of the products use phase
$Lsys$ is the lifetime of the products situation in a building system (Brand, 1994)

With this the Linear Flow Index can be calculated in the following way.

$$LFI = \frac{V + W}{2M}$$

Where
$0 \leq V \leq M$ and $0 \leq W \leq M$ and the total mass flow is equal to 2M.

The material Circularity Indicator can now be determined for each product. (Ellen MacArthur Foundation & Granta Design, 2015)

$$MCIp\ (a) = 1 - LFIp(a).F(Xp(a))$$

Where
$LFIp(a)$ is the Linear Flow Index (from the Virgin Feedstock and Waste);
$F(Xp(a))$ is the function of the utility factor $Xp(a)$; this applies

$$F(X) = \frac{a}{Xp(\alpha)}, with\ a\ is\ a\ constant$$

In the case of an almost fully linear product (LFI ≈ 1) with a shorter lifetime then the system, the MCI is negative. To prevent a negative value, the bottom-line (0) is taken into account and the final determination of MCI for a product is:

$$MCIp(\alpha) = max\ (0, (1 - LFIp(\alpha) \cdot F(Xp(\alpha))))$$

Product Circularity Indicator (PCI)
The MCI is based on the hypothesis that the BCI can be built up by a summation of all MCI_p's. However, that does not apply to PCI; the PCIp of a product would not be any realistic value since the interfaces and connections between products is of great importance for indicating the circularity of a system. Thereby, the MCI can be seen as a 'theoretical' value and the PCI as a 'practical' for a products' purpose. For the benefit of a communication model, this gives the principal the opportunity to see what the optimal value (theoretical) of PCIp could be of a product and what in that products practical value is.

The Product Circularity Indicator can be determined in the following way.

$$PCIp = \frac{1}{Fd} \sum_{i=1}^{n} MCIp \cdot Fi,$$

Where Fi is one of the DDF factors and:

$$Fd = \sum_{i=1}^{n} Fi$$

The DDF factors are adopted from a study towards Design for Disassembly by Durmisevic (2006) and are shown in the following table with the weights for each Fuzzy variable for Disassembly.

Fuzzy variable	Attribute	Weight
Functional separation	Separation of functions	1,0
	Integration of functions with the same lifecycle into one element	0,6
	Integration of functions with a different lifecycle into one element	0,1
Functional dependence	Modular zoning	1,0
	Planned interpenetrating for different solutions (overcapacity)	0,8
	Planed for one solution	0,4
	Unplanned interpenetrating	0,2
	total dependence	0,1
Technical life cycle / coordination	Long (1) / long (2) or short (1) / short (2) or long (1) / short (2)	0,1
	Medium (1) / long (2)	0,5
	short (1) / medium (2)	0,3
	short (1) / long (2)	0,1
Geometry of product edge	Open linear	1,0
	Symmetrical overlapping	0,8
	Overlapping on one side	0,7
	Unsymmetrical overlapping	0,4
	Insert on one side	0,2
	Insert on two sides	0,1
Standardisation of product edge	Pre-made geometry	1,0
	Half standardised geometry	0,5
	Geometry made on the construction site	0,1
Type of connection	Accessory external connection or connection system	1,0
	Direct connection with additional fixing devices	0,8
	Direct integral connection with inserts (pin)	0,6
	Direct integral connection	0,5
	Accessory internal connection	0,4
	Filled soft chemical connection	0,2
	Filled hard chemical connection	0,1
	Direct chemical connection	0,1
Accessibility to fixings and intermediary	Accessible	1,0
	Accessible with additional operation which causes no damage	0,8
	Accessible with additional operation which is reparable damage	0,6
	Accessible with additional operation which cases damage	0,4
	not accessible - total damage of elements	0,1

Selection of Fuzzy variables by Durmisevic (2006) implemented in the BCI (Verberne, 2016)

Each variable is independent and can therefore cause the same amount of impact. This assumption is made because no research makes such a distinction.

System Circularity Indicator

To aggregate all the $MCIp$ (theoretical) and $PCIp$ (practical) for a number (n) of products, towards a systematic value, normalised factors are used to determine a weighted average of each product for the SCI.

The equation for the theoretical value of SCIs(t) for a system (s) is then as follows:

$$SCIs(t) = \frac{1}{Ws}\sum_{j=1}^{n} MCIj \cdot Wj\ ,$$

Where MCI_j the Material Circularity Indicator for a product *j*.

The equation for the practical value of SCIs(p) for a system s is then as follows:

$$SCIs(p) = \frac{1}{Ws}\sum_{j=1}^{n} PCIj \cdot Wj\ ,$$

both with, Wj the product mass of product j, and:

$$Ws = \sum_{j=1}^{n} Wj$$

Where Ws is the total product mass of the product rang (*j, n*).

Building Circularity Indicator

the circularity of products with a shorter lifetime is more relevant than products with a longer lifetime (e.g. for the stuff layer (5 years) is circularity more important than for the structure layer (100 years)). Therefore, based on the building layers of Brand (1994), a level of importance could be assigned per system. The fuzzy variables of Durmisevic (2006) could also be applied in relation with the system lifetime presented by the research of Brand (1994),

System dependency	Stuff	1,0
	Space plan	0,9
	Services	0,8
	Skin	0,7
	Structure	0,2
	Site	0,1

In order to determine the Building Circularity Indicator, all the System Circularity Indicators (both practical and theoretical) and weighted variables should be aggregated to one specific value. Determination of the BCI for one building can be done using the following formulas:

$$BCI(t) = \frac{1}{LK}\sum_{k=1}^{n} SCI(t)k \cdot LKk,$$

$$BCI(p) = \frac{1}{LK}\sum_{k=1}^{n} SCI(p)k \cdot LKk,$$

Where
$SCI(t)k$ is the theoretical value System Circularity Indicator and,
$SCI(p)k$ is the practical value for the System Circularity Indicator for a system k,
LKk is the factor for the system dependency, and:

$$LK = \sum_{k=1}^{n} LKk,$$

Where
LK is the summation of the system dependencies.

Preconditions and drivers
The preconditions and drivers set in the Building Circularity Indicator are not included in the Building Circularity Indicator calculation method and are therefore excluded in this appendix.

Appendix 2: Questionnaire Survey I

Enquête afstudeeronderzoek losmaakbaarheid

Beste lezer,

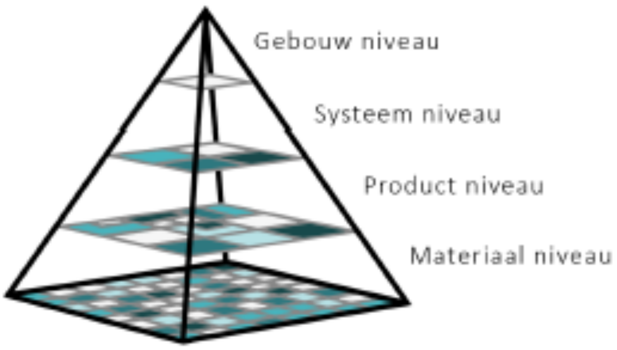
Deze enquête is onderdeel van mijn afstudeeronderzoek naar de invloed van losmaakbaarheid van een gebouw op de circulariteit van een gebouw. De potentie van losmaakbaarheid van een gebouw is een indicatie in hoeverre er rekening is gehouden met de mogelijkheid tot demontage aan het eind van de levenscyclus van het gebouw. Demontage is een belangrijke handeling om materiaal te hergebruiken.

Door middel van vooronderzoek is een lijst met factoren opgesteld die invloed kunnen hebben op de losmaakbaarheid potentie van een gebouw. Een aantal factoren zijn uitgelegd in tekst en bij een aantal factoren wordt deze tekst ondersteund door voorbeelden.

Dit is de eerste enquête in een reeks van drie waarin wordt gevraagd of de voorgestelde factoren in uw opinie belangrijk zijn om losmaakbaarheid te waarborgen in een bouwproject.

* Required

Componenten niveaus



1. **Wat is de core business van het bedrijf waar u werkt?** *
   Mark only one oval.
   - ◯ Voorbereiding (initiatief tot en met aanbesteding)
   - ◯ Realisatie (start bouwvoorbereiding tot en met oplevering)
   - ◯ Exploitatie (start in gebruik name tot en met einde levensduur)
   - ◯ Sloop
   - ◯ Other: ____________________

2. **Tolerantie** *
   Hoe belangrijk is de aanwezigheid van tolerantie (speling) tussen componenten om losmaakbaarheid te waarborgen?
   Mark only one oval.
   - ◯ Altijd belangrijk
   - ◯ Soms belangrijk
   - ◯ Onbelangrijk

3. **Methode van fabricatie** *

Hoe belangrijk is het dat componenten geprefabriceerd worden buiten de bouwplaats in plaats van volledig gefabriceerd worden op de bouwplaats om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

4. **Type bevestiger** *

Hoe belangrijk is het type bevestiging dat gebruikt wordt om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

5. **Toegankelijkheid van de bevestiger** *

Hoe belangrijk is de fysieke toegankelijkheid van bevestigingen om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

6. **Coördinatie van levensduren**

Hoe belangrijk is het dat materialen met de langste levensduur eerder worden gemonteerd en vervolgens materialen met een kortere levensduur om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

7. **Materiaal kwaliteit** *

Hoe belangrijk is de materiaalkwaliteit om aan te sporen om op demontage over te gaan in plaats van slopen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

8. **Gevaarlijkheid materialen** *

Hoe belangrijk is het vermijden van het gebruik van gevaarlijke stoffen in een gebouw om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

9. **Demontage instructies** *

Hoe belangrijk is het ontwikkelen van demontage instructie voor het gehele project om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

10. **Codering en markering** *

Hoe belangrijk is het coderen en markeren van componenten om demontage instructies beschikbaar te maken om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

11. **Aantal bevestigingen** *

Hoe belangrijk is het minimaliseren van het aantal gebruikte bevestigingen tussen componenten om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

12. **Gebruikers participatie** *

Hoe belangrijk is (intensieve) participatie van de gebruiker tijdens het gebouw ontwikkelproces om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

13. **Tijdsduur van demontage** *

Hoe belangrijk is de tijdsduur van demontagehandelingen om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

14. **Kosten van demontage** *

Hoe belangrijk zijn de kosten van demontagehandelingen om losmaakbaarheid te waarborgen?
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

15. **Aantal demontage handelingen** *

Hoe belangrijk is het minimaliseren van het aantal demontage handelingen die benodigd zijn om losmaakbaarheid te waarborgen?

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

16. **Benodigd gereedschap** *

Hoe belangrijk is het dat het benodigde gereedschap om te demonteren zo standaard mogelijk is om losmaakbaarheid te waarborgen?

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

17. **Kennis van de demonteur** *

Hoe belangrijk is de aanwezige kennis van de demonteur in het deconstructie proces om losmaakbaarheid te waarborgen?

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

18. **Veiligheid** *

Hoe belangrijk zijn de veiligheidsmaatregelingen op de bouwplaats tijdens demontage werkzaamheden om losmaakbaarheid te waarborgen?

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

19. **Hanteerbaarheid** *

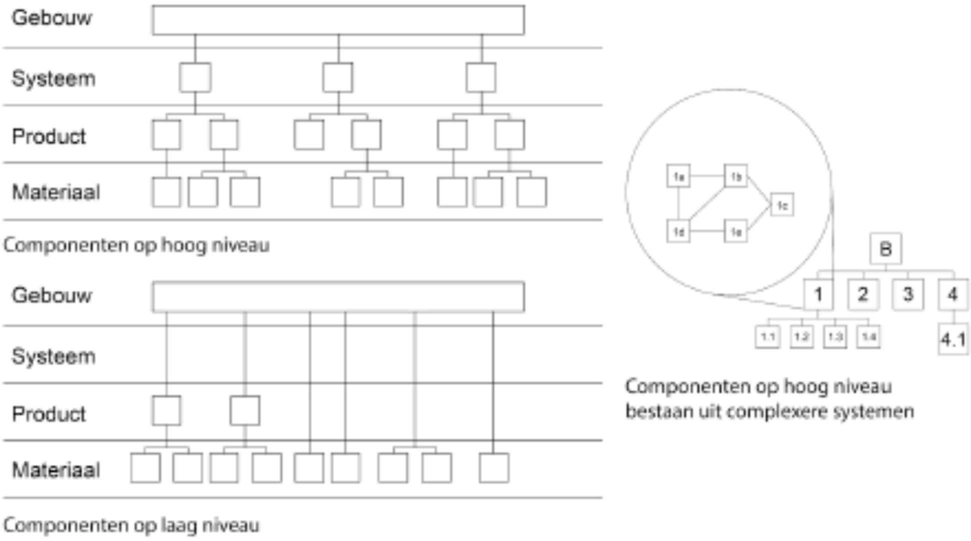
Hoe belangrijk is het dat componenten zo worden toegepast dat deze niet te groot zijn, zodat deze tijdens de demontage makkelijk hanteerbaar zijn om losmaakbaarheid te waarborgen?

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

20. **Niveau van componenten** *

Hoe belangrijk is het dat componenten zoveel mogelijk worden uitgevoerd met componenten van een hoog niveau om losmaakbaarheid te waarborgen? Het gevolg is dat hierdoor minder relaties ontstaan op de bouwplaats.

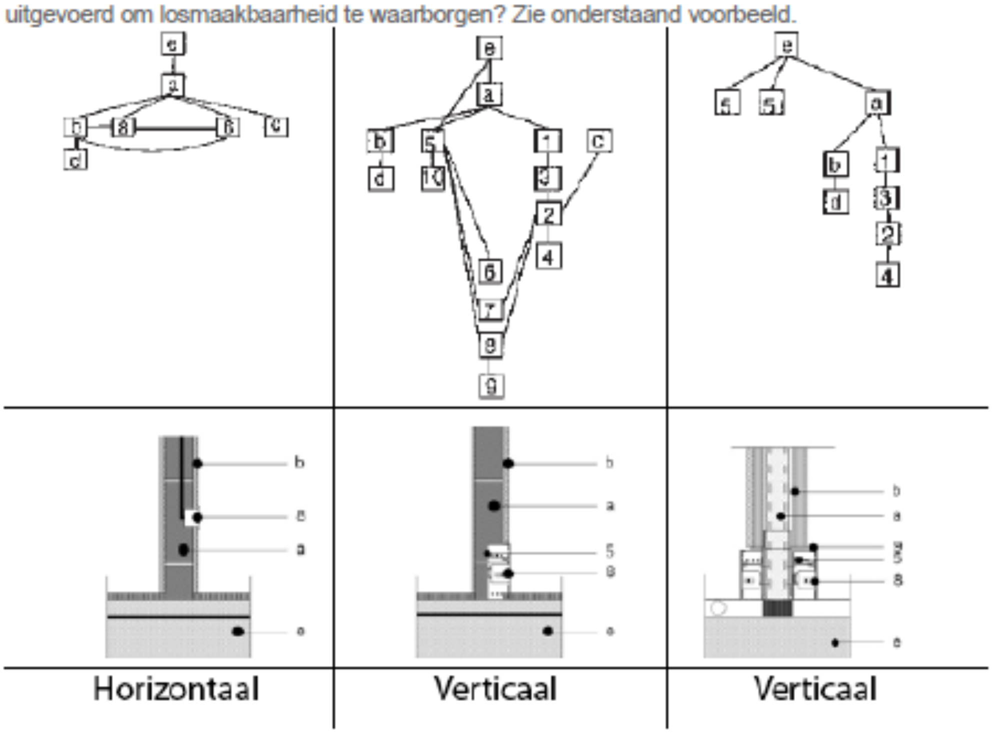


Mark only one oval.

- ◯ Altijd belangrijk
- ◯ Soms belangrijk
- ◯ Onbelangrijk

21. **Relatie patroon** *

Hoe belangrijk is het om te zorgen dat connecties zoveel mogelijk hiërarchisch worden uitgevoerd om losmaakbaarheid te waarborgen? Zie onderstaand voorbeeld.

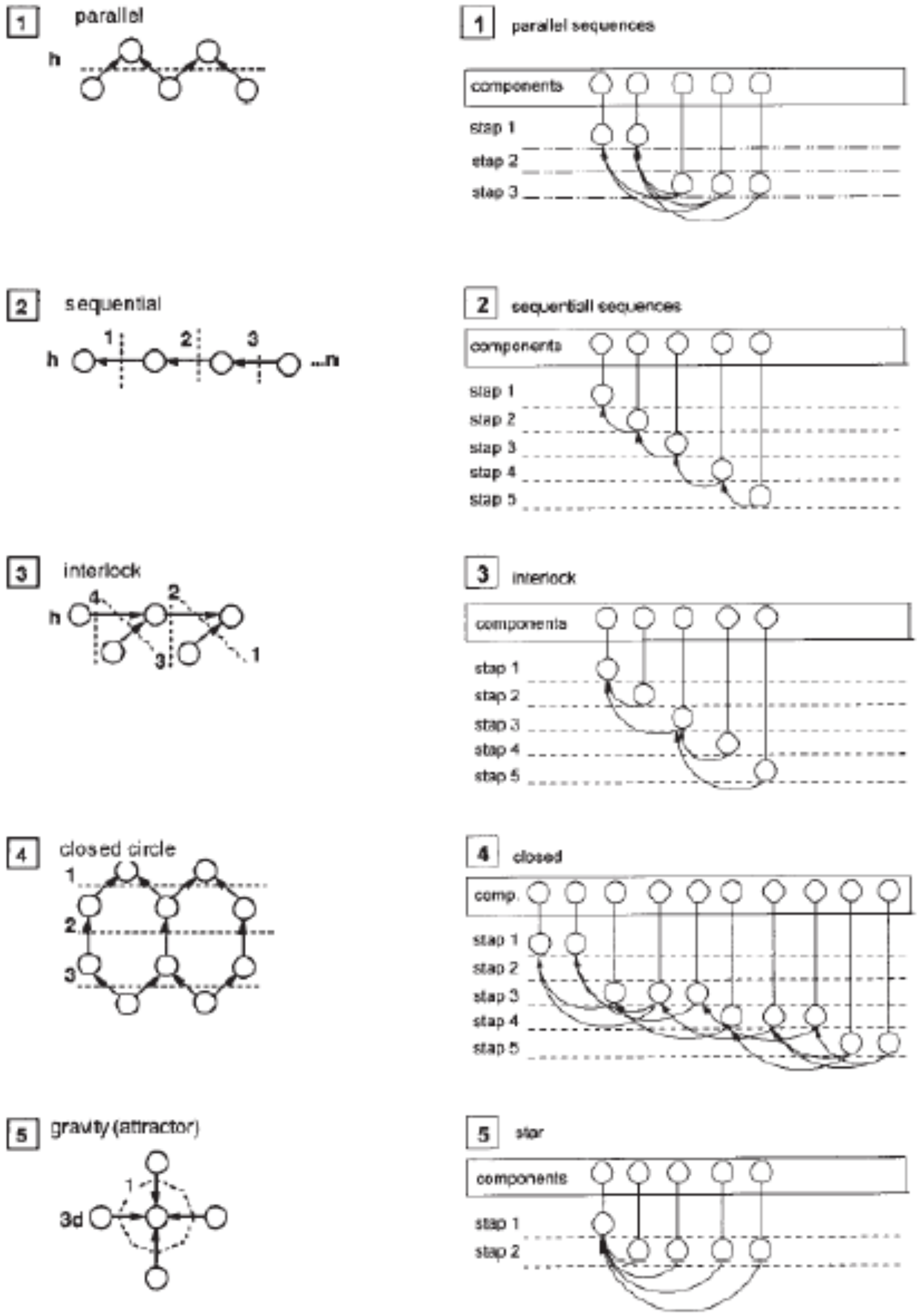


Mark only one oval.

- ◯ Altijd belangrijk
- ◯ Soms belangrijk
- ◯ Onbelangrijk

22. **Montage richting** *

Hoe belangrijk is het dat componenten parallel aan elkaar gemonteerd worden, zodat verschillende componenten gelijktijdig weer gedemonteerd kunnen worden om losmaakbaarheid te waarborgen?

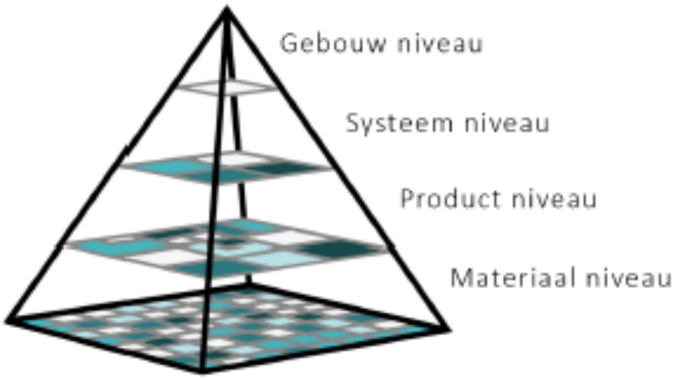


Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

23. **Montage volgorde** *

Hoe belangrijk is het dat componenten met een hoger componenten niveau eerder gemonteerd worden dan componenten met een lager componenten niveau, zodat bij demontage de componenten met een lager niveau eerder gedemonteerd kunnen worden om losmaakbaarheid te waarborgen?

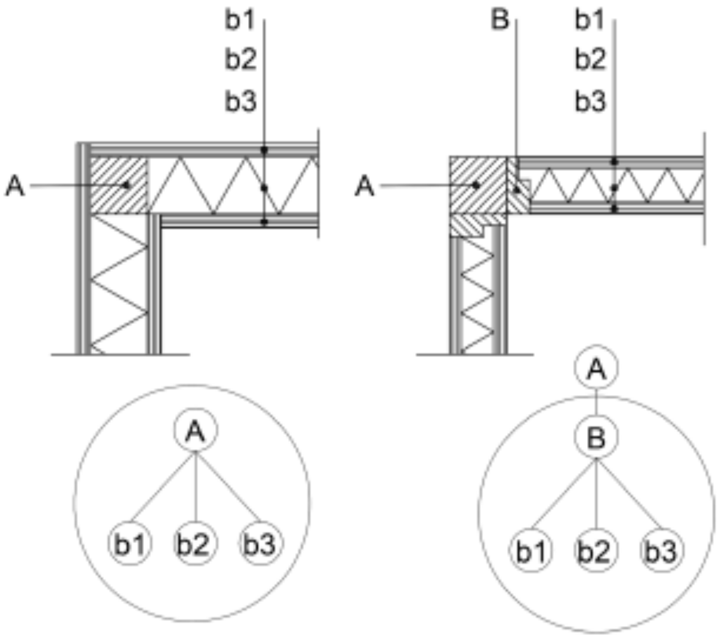


Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

24. **Toepassing van tussenelement** *

Als twee of meerdere componenten met een verschillende functie met elkaar worden verbonden, hoe belangrijk is het dat een tussencomponent wordt toegepast om losmaakbaarheid te waarborgen?



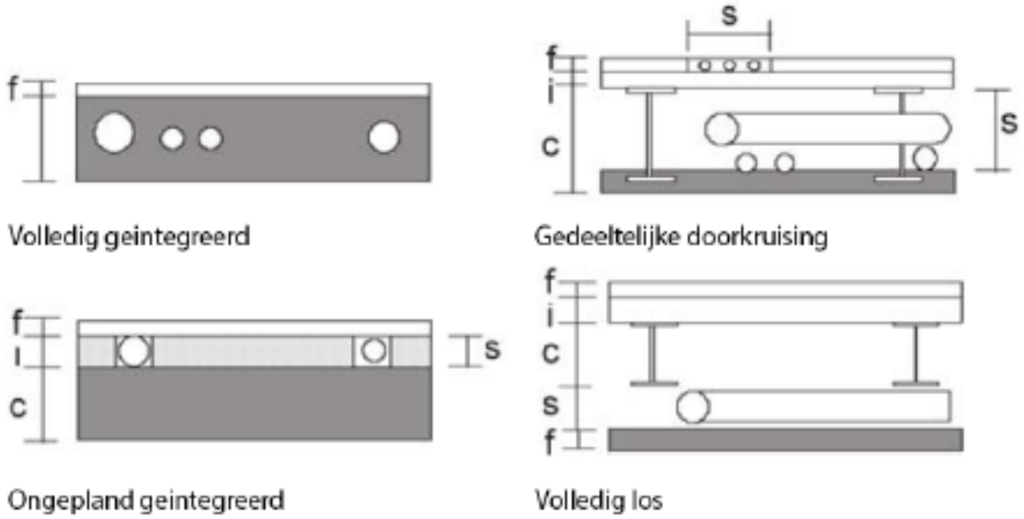
B = Tussencomponent

Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

25. **Doorkruising van componenten** *

Hoe belangrijk is het dat componenten elkaar fysiek niet doorkruisen om losmaakbaarheid te waarborgen?

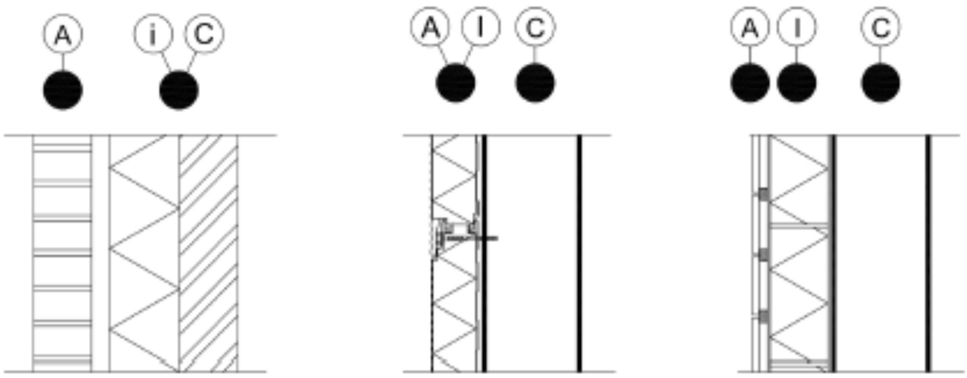


Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

26. **Scheiding van functies** *

Een gebouw component kan één of meerdere functies hebben zoals: draagstructuur, isoleren, afwerking, installatie, etc. Hoe belangrijk is het dat deze functies gescheiden worden over verschillende componenten om losmaakbaarheid te waarborgen?

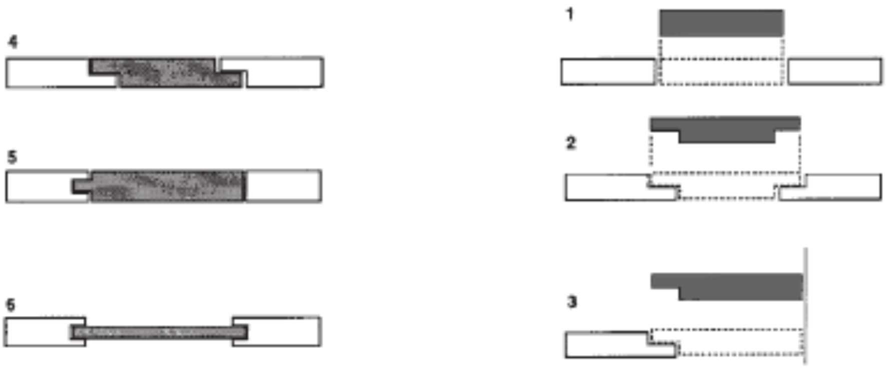


A: Afwerking
I: Isolatie
C: Constructie

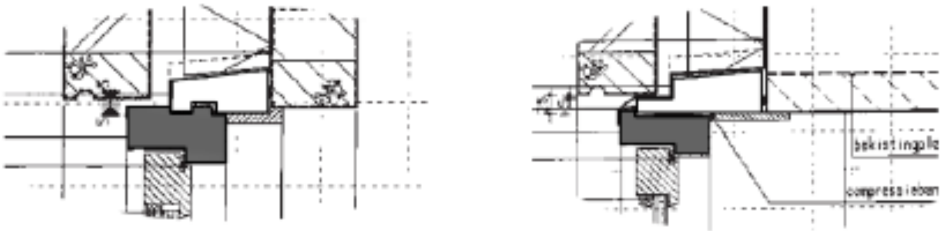
Mark only one oval.

- Altijd belangrijk
- Soms belangrijk
- Onbelangrijk

27. **Vorm van samenstelling** *
Hoe belangrijk is het dat een component niet fysiek ingesloten wordt maar dat deze open blijft aan minimaal één kant om losmaakbaarheid te waarborgen?



Gesloten Open



Gesloten Open

Mark only one oval.

- ( ) Altijd belangrijk
- ( ) Soms belangrijk
- ( ) Onbelangrijk

28. **Overige factoren**
Zijn er nog andere factoren van belang die in deze lijst niet zijn behandeld?
Mark only one oval.

- ( ) Ja *Skip to question 29.*
- ( ) Nee *Skip to question 31.*

29. **Kunt u een beschrijving geven van deze factor(en)**

30. **Hoe belangrijk is dit voor u om losmaakbaarheid te waarborgen?**

Mark only one oval.

- ( ) Altijd belangrijk
- ( ) Soms belangrijk
- ( ) Onbelangrijk

Wilt u ook deelnemen aan deel 2 van dit onderzoek?

Hiermee kunt u een belangrijke bijdrage leveren aan dit onderzoek en kost u slechts 10 minuten. U krijgt ook de resultaten van het onderzoek per mail.

31. **Zo ja, wat is uw email adres?**

Uw email adres wordt uitsluitend gebruikt om u de enquête toe te sturen. Deze zal dus nergens anders worden gebruikt en na het onderzoek zal uw email adres verwijderd worden.

____

Appendix 3: Questionnaire Survey II

Enquête over de invloed van losmaakbaarheidsfactoren op de Building Circularity Index - II

Het onderzoek

Beste lezer,

Deze enquête is onderdeel van mijn afstudeeronderzoek. Het doel van dit onderzoek is om de invloed van losmaakbaarheid van gebouwen op de Building Circularity Index te bepalen. Het doel van de enquete is tweeledig:

- Het identificeren van factoren identificeren die losmaakbaarheid beïnvloeden;
- Het bepalen van het gewicht van de factoren.

Door middel van vooronderzoek heb ik de factoren die losmaakbaarheid beïnvloeden geïdentificeerd en gevalideerd.

Op basis van de volgende vragen ga ik de gewichten van de factoren bepalen. Het beantwoorden van de vragen kost u circa 10 minuten van uw tijd.

Alvast bedankt.

Mike van Vliet

In welke projectfase bent u werkzaam?*

- ○ Voorbereiding (initiatief tot en met aanbesteding)
- ○ Realisatie (Start bouwvoorbereiding tot en met oplevering)
- ○ Exploitatie (Start ingebruikname tot en met einde levensduur)
- ○ Sloop (Start sloopinitiatief tot en met verkoop (vrijgekomen) sloopmaterialen)
- ○ Ik ben student / docent

*Kies de projectfase die het meest van toepassing is op uw werkzaamheden.

Volgende

De enquête

Dit is de **enige** pagina met vragen over factoren. Hierna volgt nog een pagina met afsluiting van de enquête.

Wilt u de mate van belangrijkheid van een factor uitdrukken met een bandbreedte? De aanpak is als volgt:

- U selecteert per factor de ondergrens en de bovengrens van de bandbreedte.
- U selecteert de meest voorkomende mate van belangrijkheid van een factor.

In totaal vult u dus drie scores in zoals in het voorbeeld hieronder. De bandbreedte reikt van *"onbelangrijk"* tot *"belangrijk"*. De meest voorkomende mate van belangrijkheid is *"neutraal"*.

Factor	Heel onbelangrijk		Onbelangrijk		Neutraal		Belangrijk		Heel belangrijk
Losmaakbaarheid	☐	☐	☑	☐	☑	☐	☑	☐	☐

Beweeg uw muis over de factor om een uitgebreide uitleg te weergeven.

Hoe belangrijk zijn naar uw idee de volgende factoren voor de losmaakbaarheid (demonteerbaarheid) van gebouwen?

Factor	Heel onbelangrijk	Onbelangrijk	Neutraal	Belangrijk	Heel belangrijk
Methode van fabricatie					
Type bevestiger					
Toegankelijkheid van de verbinding					
Relatie patroon					
Doorkruising van componenten					
Vorminsluiting					
Kosten van demontage					
Veiligheid op de bouwplaats					
Demontage instructies					
Aantal demontage handelingen					
Kennis van de 'demonteur'					
Montage volgorde					

Vorige Volgende

Einde enquête

Dit is de laatste pagina van de enquête. Bedankt voor uw input en tijd.

Heeft u interesse in de resultaten na afloop van mijn onderzoek? Laat dan hieronder uw e-mailadres achter. Zodra mijn onderzoek is afgerond, ontvangt u via e-mail de resultaten.

Email adres

Email adres:

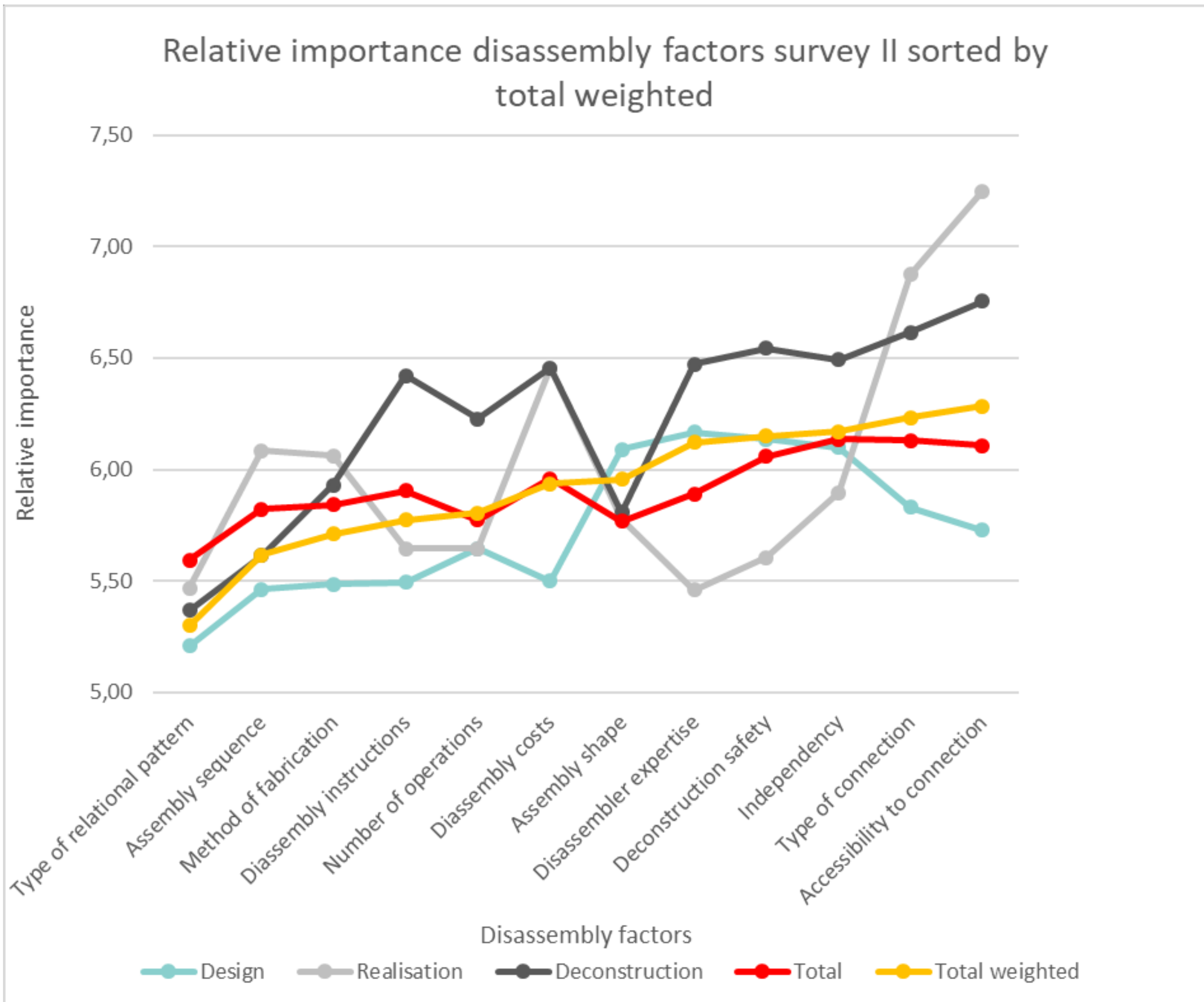
Door op voltooien te klikken verzendt u de enquête en kunt u geen aanpassingen meer doen. U kunt de pagina hierna afsluiten.

Met vriendelijke groet,

Mike van Vliet

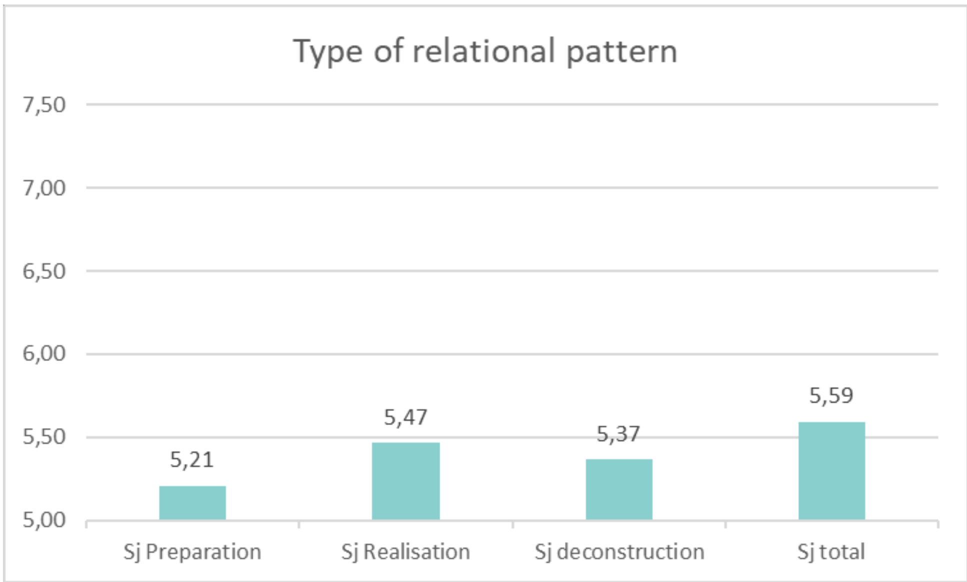
Vorige Voltooien

Appendix 4: Comparison results survey II per expert group for disassembly factors



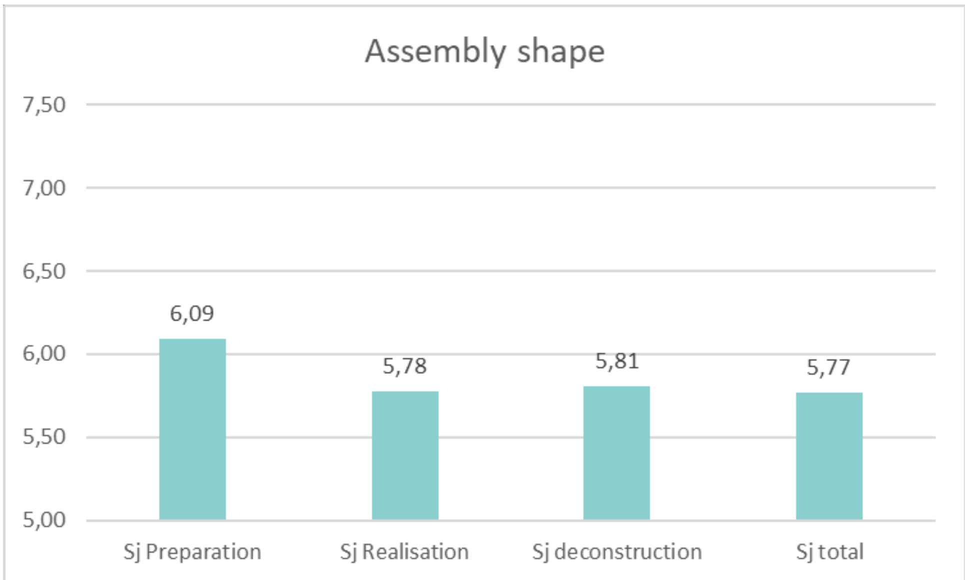
Singular derived number for each expert group and each disassembly factor

The factor 'Type of relational pattern' is considered the least important factor for all expert groups. It was also the lowest ranked in survey I of all the factors that are considered in this survey and therefore it matches the expectations. The factor is considered to be relevant in the design phase but the preparation expert group considers it slightly less important than the other expert groups. Overall this difference is negligible so this is considered as an acceptable result.



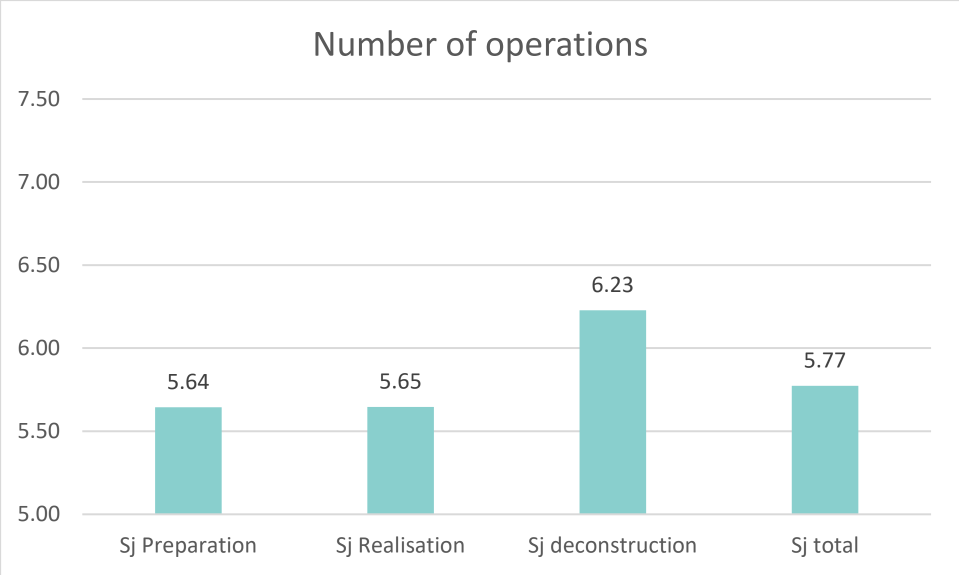
Single derived number for each expert group and in total for 'Type of relational pattern'.

The 'Assembly shape' defines whether a component is enclosed (e.g. by other components) This is dependent on the design of the construction details and therefore important during the preparation phase. Both the realization and the deconstruction expert group consider it equally important while the preparation expert group considers it more important. This is an expected result although it is notable that this is the only factor that is related to the design phase that is considered more important compared to the total single derived number.



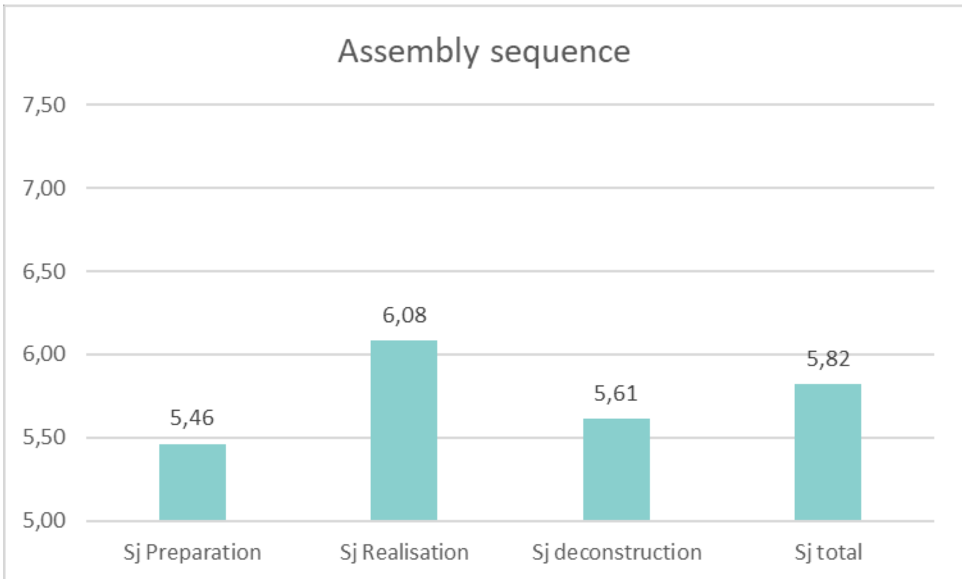
Single derived number for each expert group and in total for 'Assembly shape'.

The number of operations is related to the deconstruction phase. The results of this factor follow the assumptions that the deconstruction expert group finds this more important, because it directly relates to their activities. Furthermore there is close to no difference of importance between the other two expert groups.



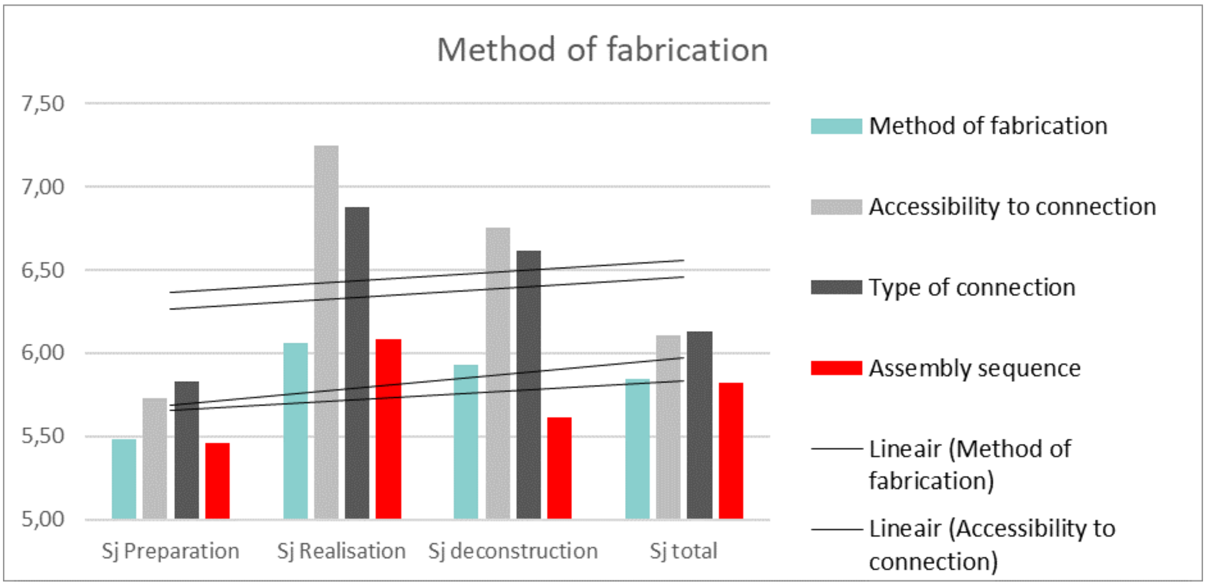
Single derived number for each expert group and in total for 'Number of operations'.

'Assembly sequence' is a technical factor and is considered a factor for design. During the design phase the building method or construction detail defines the assembly sequence. However because it considers 'assembly' it is not a surprise that the realization phase finds this to be more important. and it refers back to their primary activity which is to assemble a building. It is a more practical result of the design decisions and maybe something the expert in the preparation pay less attention to. The results for the deconstruction and design phase are close to each other. This shows that for the deconstruction phase, other aspects are more relevant to define whether a building or component is dismountable.



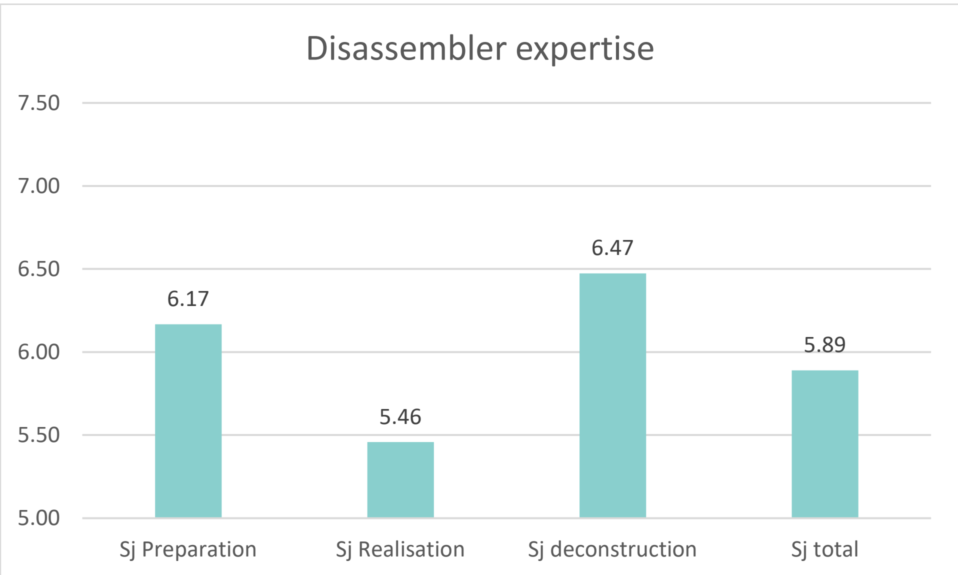
Single derived number for each expert group and in total for 'Assembly sequence'.

The method of fabrication is another technical factor for disassembly. It judges whether the assembly is entirely prefabricated or not. Prefabrication is usually related to standardization of connections, easier accessibility and higher component levels. When the results are therefore compared with the closest related factors in this research, 'Accessibility to connections', 'Type of connection' and 'Assembly sequence' (incorporation of higher and lower component levels). The linear trendlines show that method of fabrication does follow the same direction. The preparation phase finds it less important while the realization phase finds it the most important.



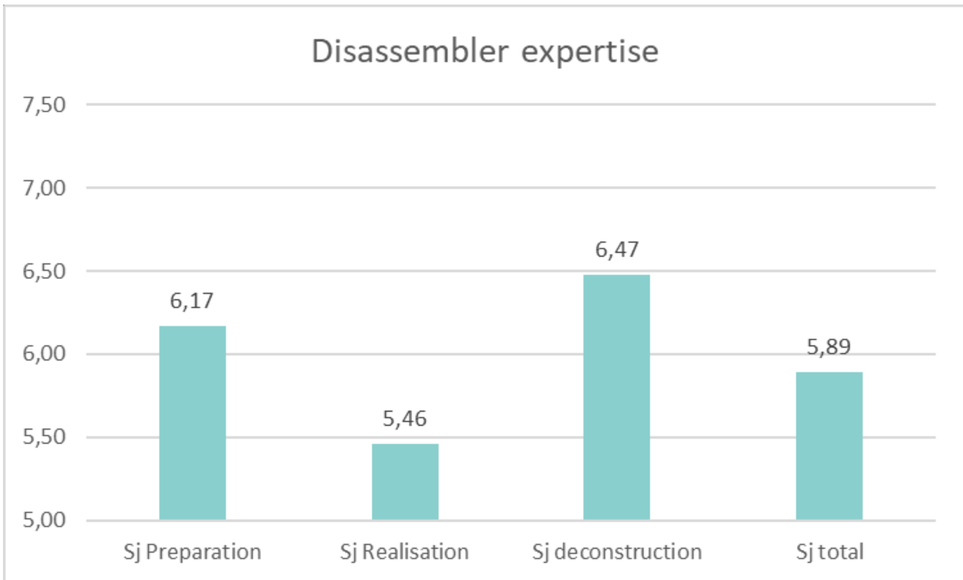
Single derived number for each expert group and in total for 'Method of fabrication' compared to 'Accessibility to connection', 'Type of connection' and 'Assembly sequence'.

The 'disassembler expertise' is the expertise of the deconstruction expert that responded to this survey. Therefore it is expected that this group finds their expertise very important. It is odd that the preparation expert group also finds this factor relatively more important than other technical factors. When the expertise of the disassembler is higher and the design meets labor practices, the incentive to disassemble instead of demolishment is higher. Maybe the experts in the preparation phase find disassembly the responsibility of the disassembler instead of a result of their design decisions. A study towards design decisions notes that the impact and importance of every design decision has to be assessed (Bragança et al., 2014) but design decisions are not always written down and "live in the head" of the designers. (A. G. J. Jansen, 2008) This could lead to an underestimation of the importance of their decision on factors for example disassembly, which is a relatively less understood principle.



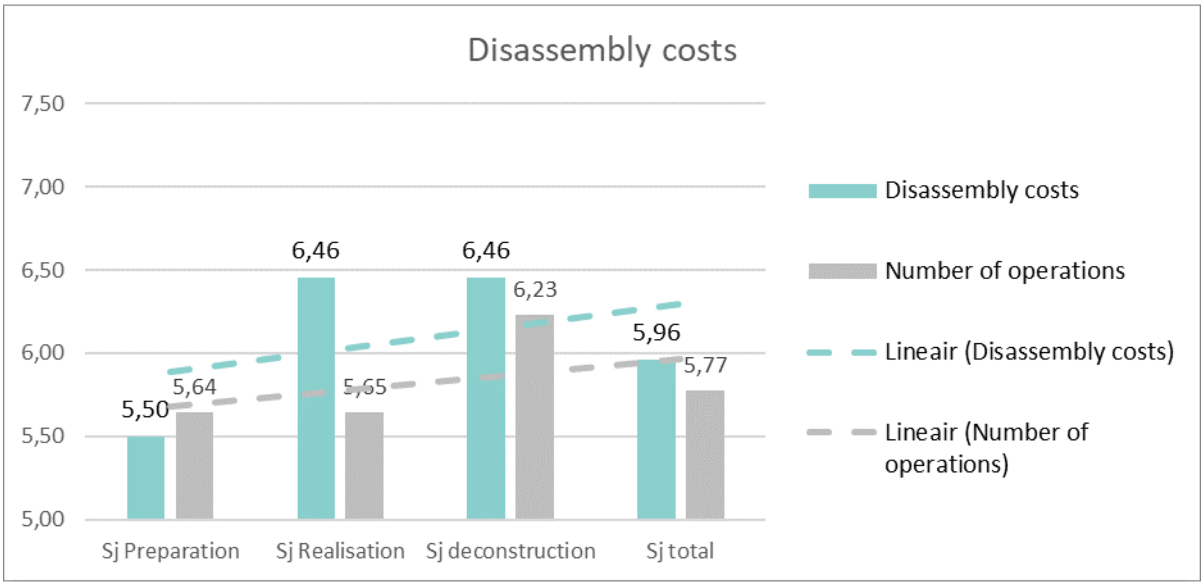
Single derived number for each expert group and in total for 'Disassembler expertise'.

Disassembly instructions is regarded as a factor for the realization phase because during this phase the instructions have to be developed for the end-of-life phase. It is expected that the deconstruction expert group finds this more important than the other expert groups because it will make their work easier. Although it is regarded to be a factor during the realisation phase it is not common practice to develop (detailed) disassembly instructions. Therefore it is expected that the realization phase finds this less important.



Single derived number for each expert group and in total for 'Disassembly instructions'.

The disassembly costs are expected to be more important to the realization and deconstruction expert groups. The difference with the first survey is however that the preparation expert group finds this factor less important than before. This also results in a lower total weight. Maybe this is because they have limited knowledge about the costs involved in disassembly or demolishment. In the end the extra investments made to perform disassembly operation (between three to eight times (Rios et al., 2015)) instead of demolishment have to be earned back through the extra value that the reutilized materials bring. The results are compared to the importance of number of operations because the extra labor required for disassembly is also considered less important by the preparation expert group. A study that compares the impact of design decision on the waste generation of a building shows that design decisions have a big impact on the amount of waste generated, and this is sometimes underestimated. (Alshboul & Ghazaleh, 2014) This study is based in a location where reduction of waste policies are not common knowledge yet. Maybe the same reasoning can be applied here, where it is difficult for the experts in the preparation expert group to assess the actual impact of their design decisions when they are realized. Especially considering a principle like disassembly which is not common knowledge yet in the Netherlands.

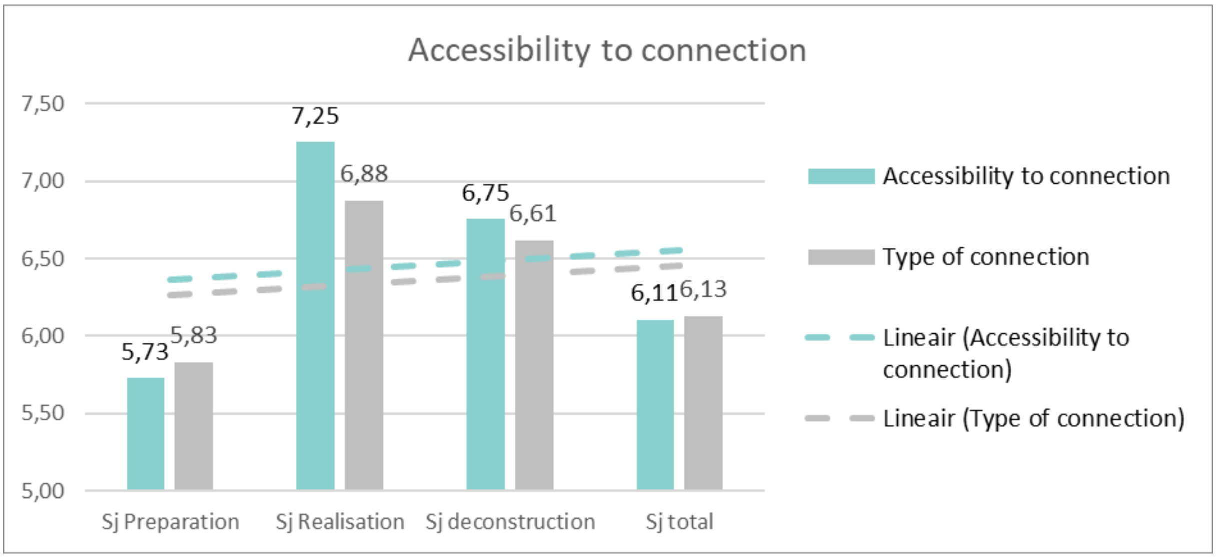


Single derived number for each expert group and in total for 'Disassembly instructions' compared to 'Number of operations'.

Deconstruction safety can be regarded as a precondition because regulations regarding safety of construction sites are extensive in the Netherlands and these have to be met. (Hoogervorst, 1999) It is expected that the deconstruction expert group finds this important because they have to comply to these conditions. It is difficult to find a reasoning from the literature why the preparation expert group finds this one of the most important principle. Extra input should be obtained to determine this. The realization expert group finds safety less important which could be because due to earlier mentioned safety regulations, it is common practice for them.

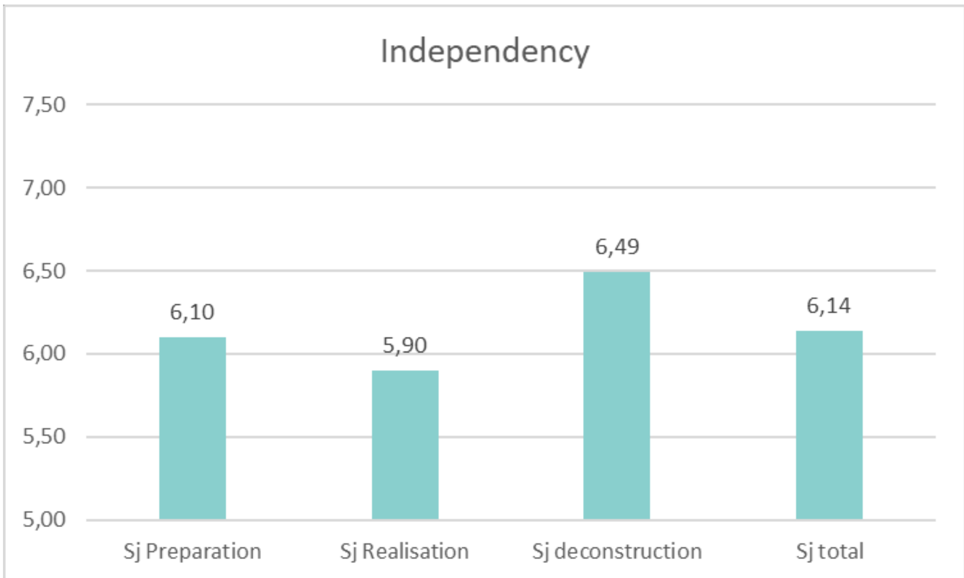
Single derived number for each expert group and in total for 'Deconstruction safety'

The accessibility to connection and type of connection is regarded as a technical factor for disassembly. When a connection is not accessible without requiring demolishment operations, it is impossible to disassemble. The construction methodology determine the accessibility and is therefore determined during the preparation phase. The realisation and deconstruction expert groups find this more important than the preparation phase. The same trend can be seen with the type of connection, this determines whether a connection is detachable or fixed. This trend is notable and an explanation why this result suddenly differs this much with the first survey I cannot explain. This requires further research to obtain the qualitative data instead of just the quantitative.



Single derived number for each expert group and in total for 'Accessibility to connection' and 'Type of connection'.

Independency became on average more important than all other factors. It is considered a technical factor and expected to be most important during the preparation phase from the literature. This factor is rated relatively high by the preparation expert group, although still lower than the deconstruction expert group. It is possible that the deconstruction experts have to deal with this more often and understand the implications independency can have on their work. It is notable that this factor is ranked as most important factor overall, compared to the seventh rank in the first survey. This is because in general the other factors are weighted relatively low by the preparation expert group, while this factor remained high. And the deconstruction expert group values this factor higher than before.



Single derived number for each expert group and in total for 'Independency'

Appendix 5: Applying the BCI in practice

During my graduation period I have worked at Alba Concepts, a consultancy for real estate development and project management. Alba Concepts helped during the development of the Building Circularity Indicator assessment model (Verberne, 2016) and is a company that actively pursues the transition towards a circular building economy.

Alba Concepts actively use the BCI to help them and clients to develop circular buildings. Furthermore they promote the BCI to other stakeholders in the built environment to help their circular ambitions. (Alba Concepts, 2018)

Projects assessed with the Building Circularity Indicator

Several buildings have been developed for which the circularity potential is measured and controlled with the Building Circularity Indicator assessment model. Alba Concepts functioned as a consultant that calculated the BCI of these projects and made recommendations for development decisions to achieve a more circular building. A brief overview of some of these project are shown discussed. These are three different types of buildings with different functions, showing the versatility that the BCI has. These projects are all new developments.

The green house, Utrecht by Cepezed

The objective is to create a facility for fifteen years. After this period the facility has to be disassembled without leaving any waste. It also reuses building materials from demolishment projects in the region. The BCI is calculated by Alba Concepts and is used to make process and design decisions. (W. Jansen, 2017)

Figure 47: The Green House, Utrecht (van der Wee, 2018)

Fijn Wonen, Gorredijk by van Wijnen
Traditional housing projects have a BCI score of around fifteen to eighteen percent. The Fijn Wonen houses have a BCI of seventy percent. A long technical lifetime of building materials and full disassembly potential are the focal points of the concept. (van Belzen, 2017) Disassembly is aimed to reuse the building components in new houses of the same concept. This focus also enables a positive waste stream scenario.

Figure 48: Fijn Wonen circulair housing (van Wijnen, 2018)

Pit Lab, Amsterdam by DOOR Architecten
In this project, organic materials, reused sea containers and window frames are applied to develop circular workplaces. This results in a BCI of sixty-seven percent. Because of the properties of the materials it is easy to disassemble and relocate the building. (van Hulten, 2017)

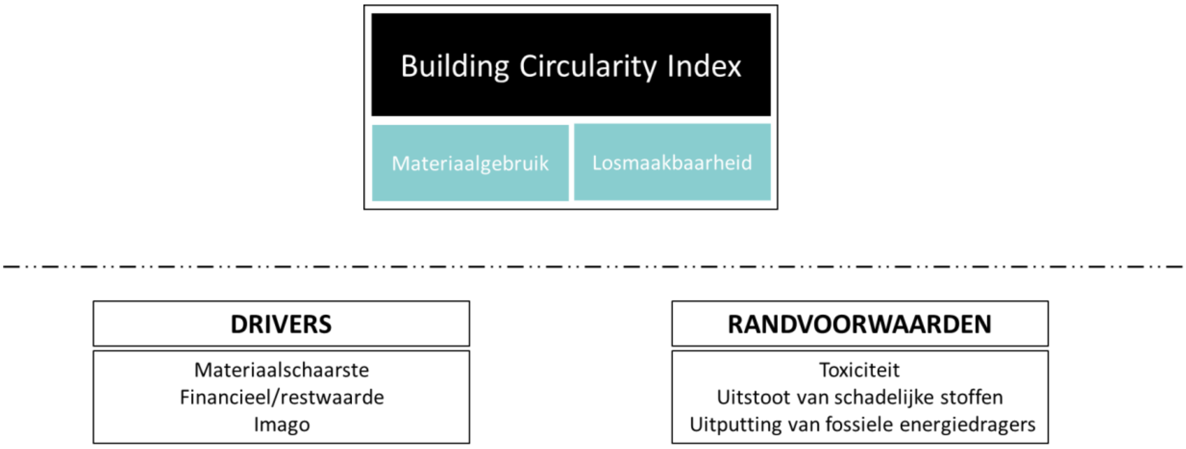
Figure 49: PIT lab, Amsterdam Tuin van BRET (van Esch, 2017)

These projects represent successful cases for the applicability of the BCI in practice. Because of the universal approach it is possible to assess all types of buildings, from houses to office buildings. When looking at the approach that these building developments have taken to enable circular material use, it is noticeable that different strategies are viable. These include but are not limited to:

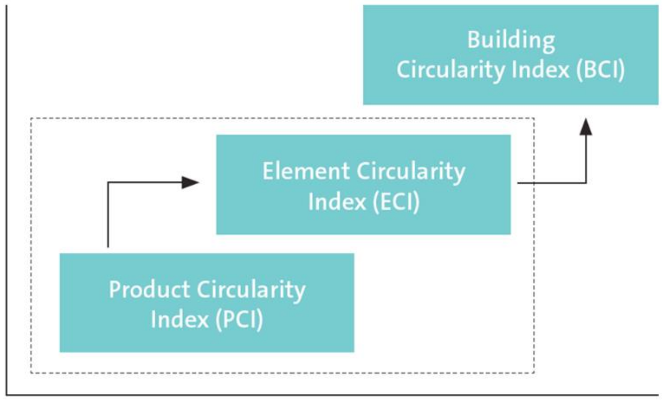
- reusing old building materials (selecting materials (Cheshire, 2016))
- Design for disassembly (Cheshire, 2016)
- Decreasing the waste stream (design out of waste (Cheshire, 2016))

Conceptual model for the BCI by Alba Concepts

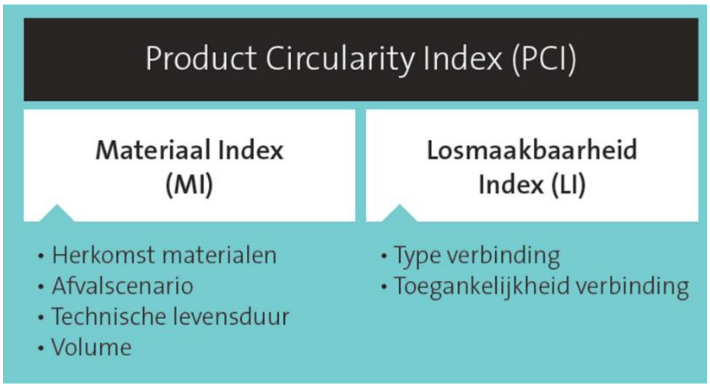
The BCI used by Alba Concepts is an adaptation of the BCI developed by Verberne (2016) to make it easier to use. The conceptual model of this adaption is shown below.



Calculation steps of the BCI



Determining the PCI



Determining the ECI

Element Circularity Index (ECI)

Herbruikbaarheid Index (FI)	Losmaakbaarheid Index (LI)

“Een element is een clustering van producten die onlosmaakbaar met elkaar verbonden zijn. Pas op het moment dat een verbinding losmaakbaar is en de schade beperkt blijft, eindigt de clustering en vormt het een element.”

Criteria for determining the Elements by Alba Concepts

“Een element is een clustering van producten die onlosmaakbaar met elkaar verbonden zijn. Wanneer het demonteren of remonteren van een product een schade veroorzaakt van meer dan 20% van de bouwkosten, is een product onlosmaakbaar. De beoordeling heeft betrekking op de verbinding/ toegankelijkheid van de verbinding aan het achterliggende product.”

Determining the Disassembly potential

Type verbinding		Score
Droge verbinding	Droge verbinding	1,0
	Klikverbinding	1,0
	Klittenbandverbinding	1,0
	Magnetische verbinding	1,0
Verbinding met toegevoegde elementen	Bout- en moerverbinding	0,8
	Veerverbinding	0,8
	Hoekverbindingen	0,8
	Schroefverbinding	0,8
	Verbindingen met toegevoegde verbindingselementen	0,8
Directe integrale verbinding	Pin-verbindingen	0,6
	Spijkerverbinding	0,6
Zachte chemische verbinding	Kitverbinding	0,2
Harde chemische verbinding	Lijmverbinding	0,1
	Aanstortverbinding	0,1
	Lasverbinding	0,1
	Cementgebondenverbinding	0,1
	Cemische ankers	0,1
	Harde chemische verbinding	0,1

Toegankelijkheid verbinding	Score
Toegankelijk	1,0
Toegankelijk met extra handelingen die geen schade veroorzaken	0,8
Toegankelijk met extra handelingen met herstelbare schade	0,6
Toegankelijk met extra handelingen met veel schade >20% van de bouwkosten	0,4
Niet toegankelijk - totale schade aan beide elementen	0,1

$$LI_E = \frac{TV + ToV}{2}$$

Determining the Element Circularity Index

ECI = Materiaalindex · Losmaakbaarheidsindex

Determining the BCI

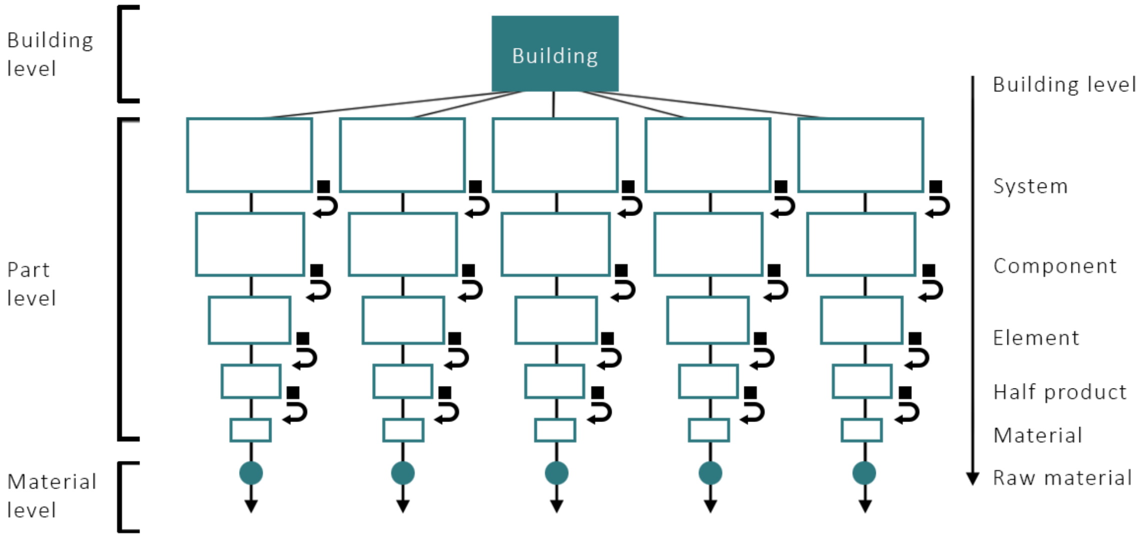
Building Circularity Index (BCI)

“Een gebouw is een combinatie van elementen. Volume wordt gebruikt als normalisatie factor.”

$$BCI = \frac{\sum m^3 * ECI}{Totaal\ volume}$$

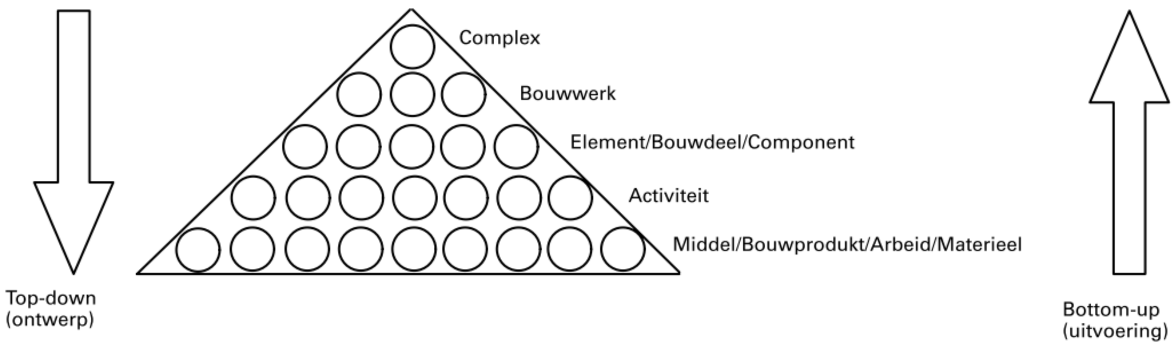
Appendix 6: Definition of building levels

The layers of Brand (Brand, 1994), the NEN 2660:1996 (NEN, 1996), the NL-SfB (BNA, 2005), the STABU method (STABU, 2015) and the Uniclass (Delany, 2015) all represent guides to classify data in the construction industry. This research aims to use a classification for building materials to differentiate between detail levels in an objective matter. This is adopted from the disassembly approach by Durmisevic (Figure 1) (Durmisevic, 2006) A combination of these methods is made to be all-inclusive. Because there is no universal standard that defines enough detail to use yet.



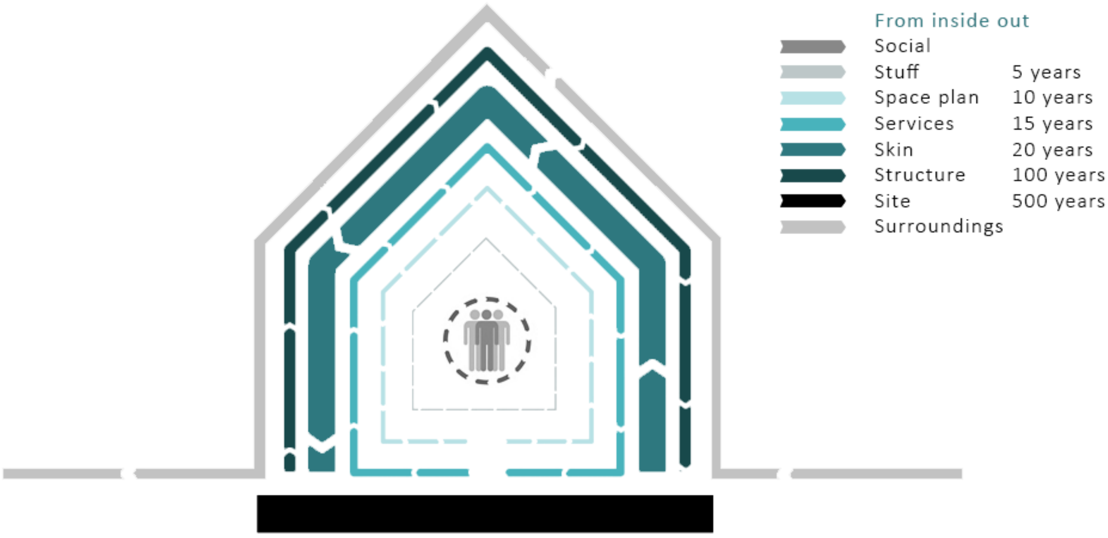
1: Theory of material levels (Durmisevic, 2006)

The NEN 2660:1996 and the theory of material levels will be used to define the names of the different detail levels.



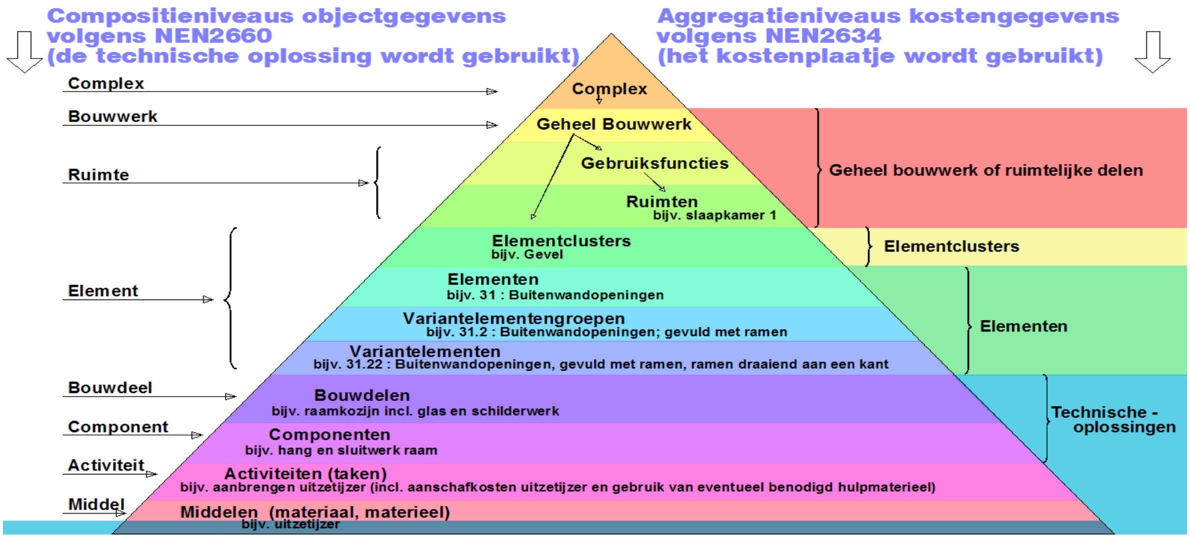
2: Information carriers for classifications (NEN, 1996)

The layers of Brand (Brand, 1994) define the starting point of classifications. It is very generic and it does not require specific definitions for everybody to classify a building material according to the layers of Brand. (Figure 3) In this research the Layers of Brand will be referred to as “Building layers”



3: Layers of Brand (Brand, 1994)

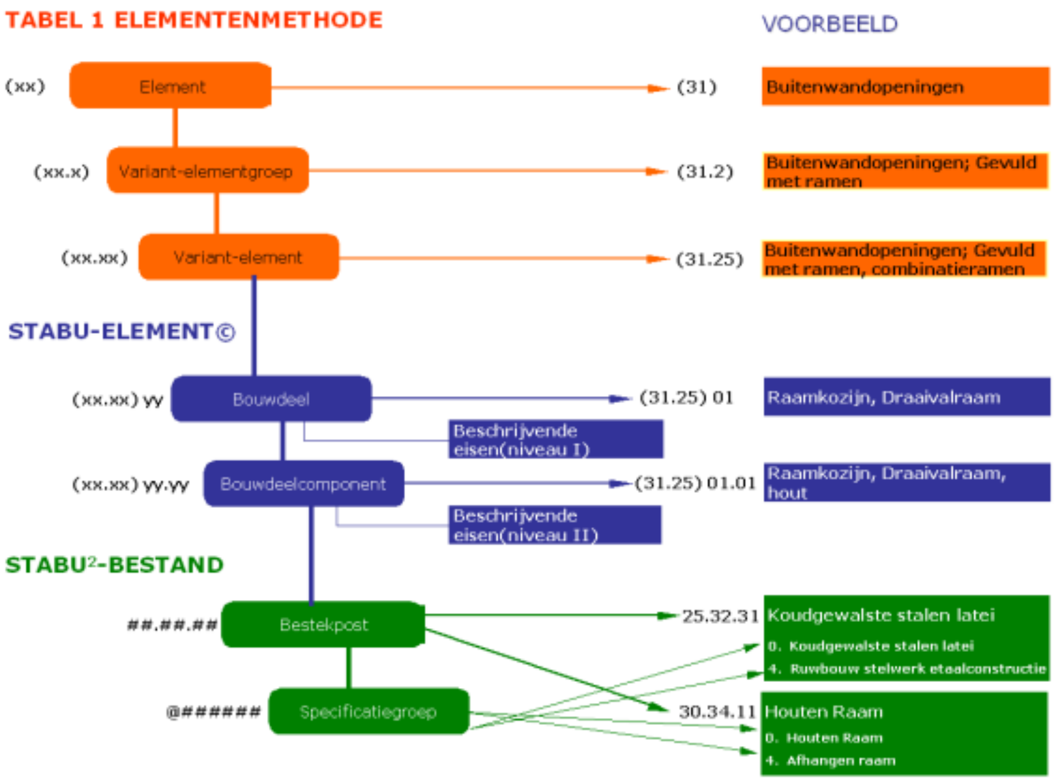
The NL/SfB elementenmethode is a bit more specific than the layers of Brand (Brand, 1994) and defines elements in a building on a few different levels. The codes can be used to objectively categorize building materials. One step lower than the building layers is the element level, the first two digits (##) of the NL/SfB defines this level. To be consistent, the definition "System level" is adopted. Another step lower is the "variant element groups" which is defined by the third digit (##.#) in the NL/SfB. The definition "Element group" is adopted. Another step lower is the "variant elements" which is defined by the fourth digit (##.##) in the NL/Sfb. The definition "Element" is adopted. This is where the original NL/SfB elementenmethode stops.



4: Composition levels object data accoding to the NEN2660:1996 with NL/SfB codes.

An addition to the NL/SfB adds two lower category defined by STABU-Element with two additional codes. One lower level compared to "Element", defined by the fifth and sixth digits (##.##.##) is Building part. The definition "product" is adopted. The major material is also defined by this digit (for example 'exterior wall' (fifth digit), 'brick' (sixth digit).

The STABU2 technical specification and conditions categorization maintains a separate coding system. (Figure 5) This coding system can be used as an addition to the coding system described above to add more levels of detail in building levels. the 'specification groups' from the 'bestekpost' can be used to determine of which components the product consists of and which materials the component is made of. These are adopted as subsequently the component level and the material level.



5: Comparison Elementenmethode, STABU-Element and STABU2-Bestand

An overview of all levels, the sources where to retrieve the information and the adopted definitions is shown in table 1.

1: Levels of details of a building with, adopted definitions with coding

Level	Source	Adopted definition	Example coding	Example description
0	Layers of Brand	Building layers		Space plan
1	NL/SfB (2 digit coding)	System level	22	Interior wall
2	NL/SfB (3 digit coding)	Element group level	22.1	Non-structural
3	NL/SfB (4 digit coding)	Element level	22.13	Fixed partition wall
4	NL/SfB (6 digit coding)	Product level	22.13.17	Metal stud wal, plasterboard
5	STABU2 (specification group)	Component level	44.41.21-X	Plasterboard
6	STABU2 (specification group)	Material level	44.41.21-X	Plasterboard
7		Raw material		Gypsum

Appendix 7: Adoption of the Fuzzy variables for disassembly by Durmisevic (2006)

Type of connection

Type of connection		
	Accessory external connection or connection system	1,0
	Direct connection with additional fixing devices	0,8
	Direct integral connection with inserts (pin)	0,6
	Direct integral connection	0,5
	Accessory internal connection	0,4
	Filled soft chemical connection	0,2
	Filled hard chemical connection	0,1
	Direct chemical connection	0,1

The type of connection as a disassembly factor is already adopted in the BCI by Alba Concepts. In this application the types of connection attributes have been made more specific towards practical connection types. All the categories remain the same except direct integral connection and accessory integral connection. This however covers all types of relations that are used in practice.

1. Type verbinding		
Dry connections (with or without accesory external connection)	Dry connection	1,0
	Click connection	1,0
	Velcro connection	1,0
	Magnetic connection	1,0
Direct connection with additional fixing devices	Bolt and nut connection	0,8
	Tongue and groove connection	0,8
	L-profile connection	0,8
	Screw connection	0,8
	Connection with additional fixing devices	0,8
Direct integral connection	Pin connection	0,6
	Nail connection	0,6
Filled soft chemical connection	Putty connection	0,2
Filled hard chemical connection	Glue connection	0,1
	Poured connection	0,1
	Weld connection	0,1
	Cement based connection	0,1
	Chemical anchors	0,1
	Hard chemical connection	0,1

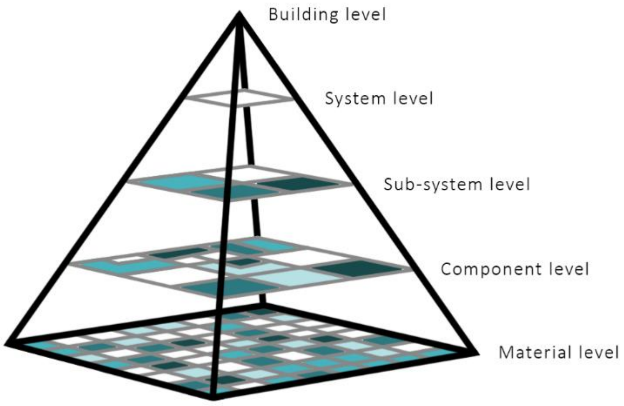
Assembly sequence

Assembly Sequence	Component (1) / Component (2)	1,0
	Component (1) / Element (2)	0,8
	Element (1) / Component (2)	0,6
	Element (1) / Element (2)	0,5
	Material (1) / Component (2)	0,3
	Component (1) / Material (2)	0,2
	Material (1) / Material (2)	0,1

Because the building levels adopted in this research are different than those adopted in the research towards Disassembly Determining Factors, the attributes for Fuzzy variables should be adjusted to fit the Building Circularity Indicator assessment model.

- System level
- Element group level
- Element level
- Product level
- Component level
- Material level

Sequences create dependencies. The way we assemble a building sets a mirror image for the way we disassemble. (Durmisevic, 2006) When considering figure 1 the building levels are hierarchical.



1: Building material levels by Durmisevic (2006)

Materials are part of components, components are part of sub-systems, etc. The factor assembly sequence is based on the theory that a product with a higher building level should be assembled before a lower building level. Setting a mirror image to disassemble products of lower building levels first.

Because this research defines more building levels than originally adopted in the Disassembly Determining Factors (Durmisevic, 2006). These cannot all be adopted as attributes because they create too much options (see below) and the differences between each other may be negligible. Further research is recommended to test out the influence of the adaption of the attributes of this variable.

Possible combinations of connecting building levels with each other.

- System / System
- System / Element group
- System / < Element group
- Element group / Element group
- Element group / Element
- Element group / < Element
- Element / Element
- Element / Product
- Element Product
- Product / < Product
- Product / Product
- Product / Component
- Product / Material
- Component / Component
- Component / Material
- Element group / System
- Element / Element group
- Element / System
- Product / Element
- Product / > Element
- Component / Product
- Component / > Product
- Material / Component
- Material / > Component

This is segregated in three attributes that catch the essence of the theory that a product with a higher building level should be assembled before a lower building level.

- Same level / Same level
- High level / Low level
- Low level / High level

Assembly sequence	The same level / the same level	1,0
	High level / Low level	0,5
	Low level / High level	0,1

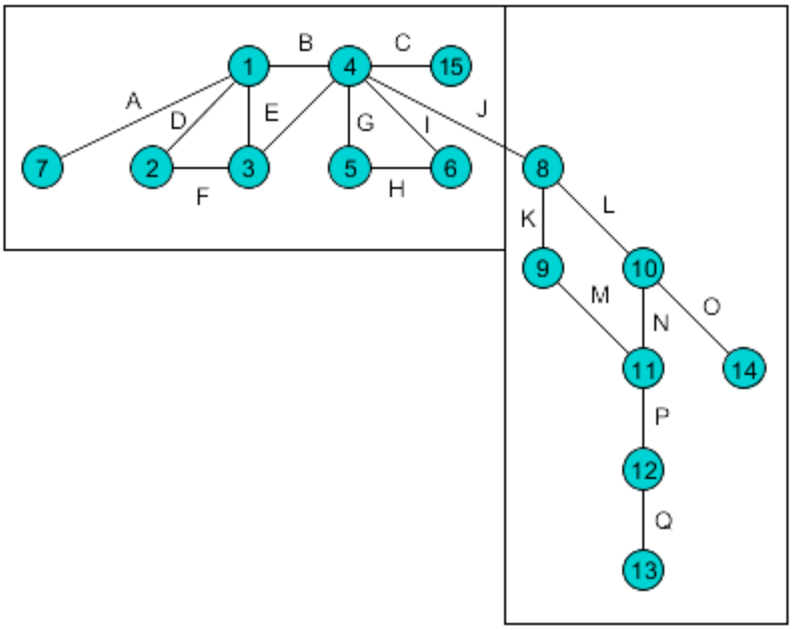
The weights of the attributes are based on a high/medium/low weighting because there is a lack of information about the importance of the attributes in this way. This is an assumption that is made to be able to assess the factor in the BCI v2.0. This research does not include assessing weighting. Therefore it is recommended that the weights are reassessed in future research.

Relational pattern

Type of relational pattern	Vertical	1
	Horizontal in lower zone of the diagram	0,6
	Horizontal in between upper a lower zone of the diagram	0,4
	Horizontal in upper zone of the diagram	0,1

The relational pattern is a factor that assesses an entire assembly. In the PCI the products are assessed based on the assembly they are in. When an assembly has a relational pattern that is horizontal in the upper vertical in the lower zone of the pattern, it would be relatively heavy to weigh all the products a 0,1 in this assembly regarding the factor for relational pattern.

The essence of relational pattern is that when products have a lot of connections between different products, the relational pattern becomes horizontal. When there is only one or two connections for a certain product, it is essentially vertical. Figure 2 shows that there are many connections in the top part, representing a horizontal pattern and the bottom part has less connections representing a vertical pattern.



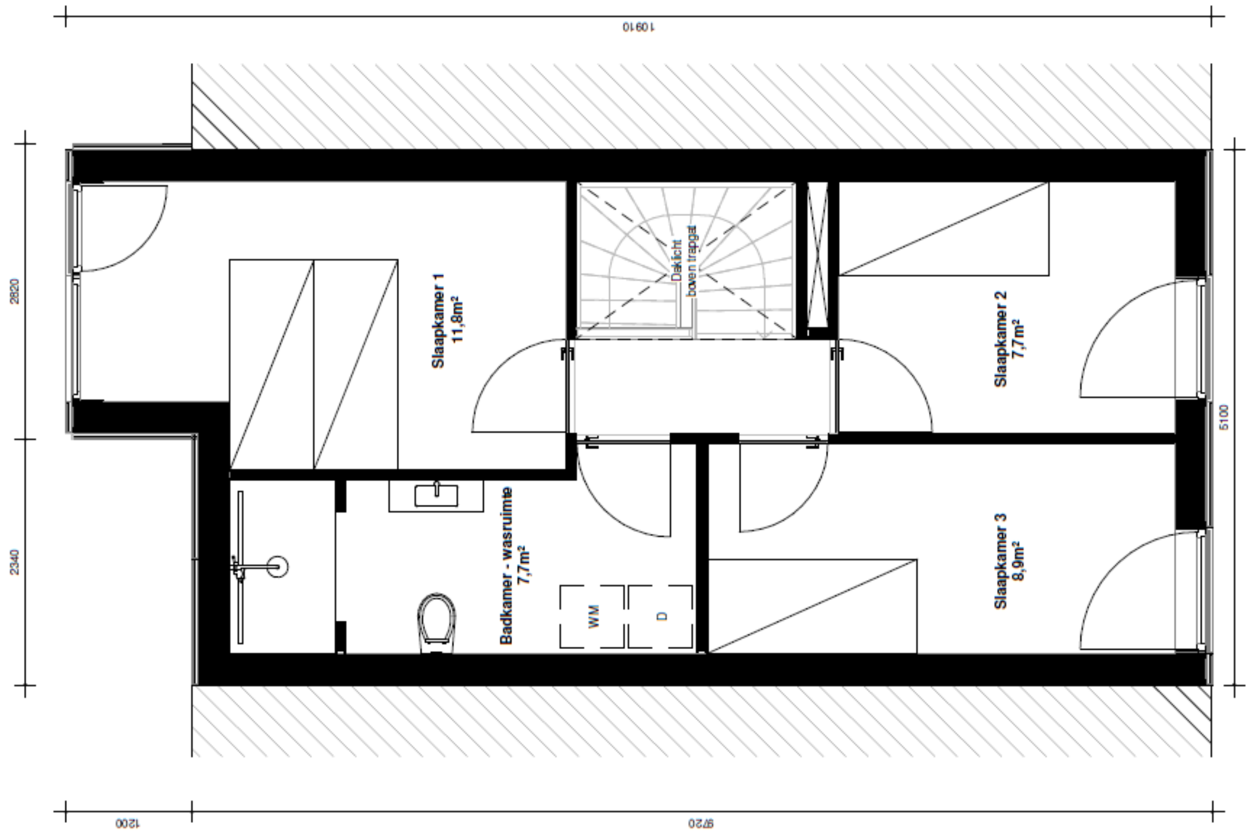
2: horizontal and vertical relational pattern

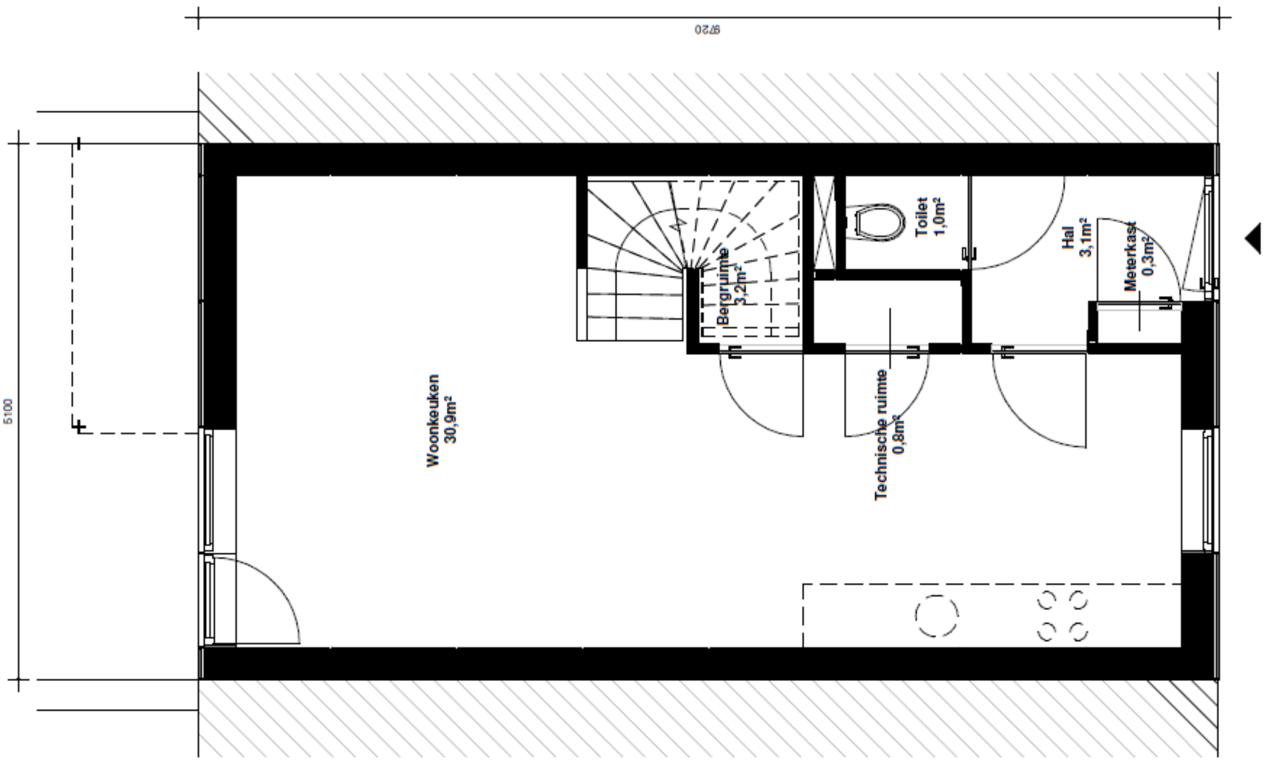
To adopt type of relational pattern as a factor for every product, the amount of connections that are made is used to assess the relational pattern. This will spread out the impact of the relational pattern among the products in an assembly instead of weighting them all the same.

The following attributes are adopted based on the number of connections between products in a relational pattern. This is an assumption that neglects the part of the factor that states in which part of the relational pattern the connection are made (top/middle/bottom). Additional research is recommended to validate the attribute weights.

Type of relational pattern	One or two connections	1
	Three connections	0,6
	Four connections	0,4
	Five or more connections	0,1

Appendix 8: Floor plans of the residential project in Gent by BI





Appendix 9: MCI building level 4

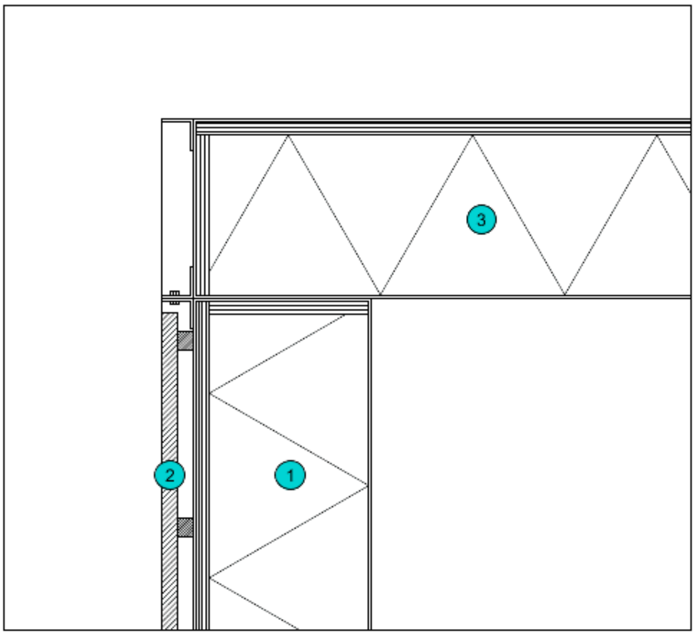
ID	L-SfB Cod	Product description	Product level	Volume (m^3)	Materials: Input: Virgin %	Materials: Input: Reused %	Materials: Output: Landfill / energy recovery (%)	Materials: Output: Reuse %	Lifecycle: Product lifecycle	Lifecycle: System lifecycle	V	W	X	LFI	Fx	MCI
21.0300.2760	21.23.18	BILT_wandpaneel	Product level	43.75			0%	100%	100	100	9.55	-	1	0.11	0.9	0.80
		Aluminium schil	Material level	0.20	40%	60%	0%	100%	100	100	0.08	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	7.46	100%	0%	0%	100%	100	100	7.46	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	33.91	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.21	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_BG	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_1e	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_dak	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
31.2.1200.276	31.25.22	BILT_Kozijnpaneel_1200mm	Product level	2.00	70%	30%	0%	100%	20	20	1.40	-	1	0.35	0.9	0.59
17.11.10	17.11.10	BILT_Schroefpaal	Product level													
22.1200.2600	22.13.31	BILT_Binnenwand_1200mm	Product level	5.00	100%	0%	12%	88%	10	10	5.00	0.60	1	0.56	0.9	0.40
32.31.21	32.31.21	BILT_Binnendeur	Component level	0.30	70%	30%	0%	100%	10	10	0.21	-	1	0.35	0.9	0.59
43.12.10	43.12.10	BILT_Verhoogdvloersysteem300x300	Product level	8.00	10%	90%	0%	100%	10	10	0.80	-	1	0.05	0.9	0.86
41.12.41	41.12.41	BILT_Buitenwandbekleding	Product level	7.00	30%	70%	30%	70%	20	20	2.10	2.10	1	0.30	0.9	0.63

Appendix 10: MCI building level 5 & 6

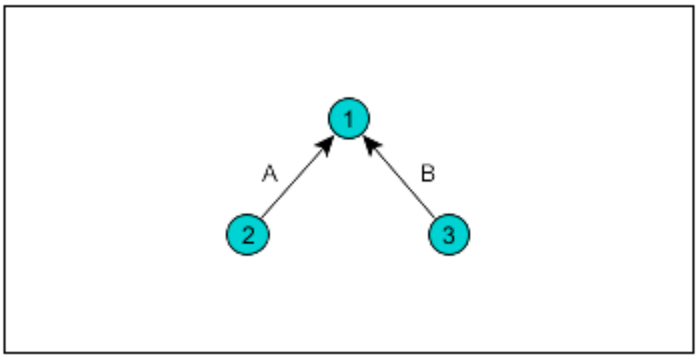
					Materials				Lifecycle		Material Circularity Indicator calculation model					
					Input		Output									
ID	NL-SfB Code	Product description	Product level	Volume (m^3)	Virgin %	Reused %	Landfill / energy recovery (%)	Reuse %	Product lifecycle	System lifecycle	V	W	X	LFI	Fx	MCI
21.0300.2760	21.23.18	BILT_wandpaneel	Product level	43.75			0%	100%	100	100	9.55	-	1	0.11	0.9	0.80
		Aluminium schil	Material level	0.20	40%	60%	0%	100%	100	100	0.08	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	7.46	100%	0%	0%	100%	100	100	7.46	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	33.91	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.21	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_BG	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_1e	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
23.0300.2400.	23.21.10	BILT_vloerpanel_dak	Product level	60.05			0%	100%	100	100	11.65	-	1	0.10	0.9	0.81
		Aluminium schil	Material level	0.25	40%	60%	0%	100%	100	100	0.10	-	1	0.20	0.9	0.72
		Multiplex schil	Material level	9.56	100%	0%	0%	100%	100	100	9.56	-	1	0.50	0.9	0.45
		Multiplex tussenschotten	Component level	1.96	100%	0%	0%	100%	100	100	1.96	-	1	0.50	0.9	0.45
		Everuse	Component level	48.09	0%	100%	0%	100%	100	100	-	-	1	-	0.9	0.90
		Extrusieprofiel	Material level	0.19	20%	80%	0%	100%	100	100	0.04	-	1	0.10	0.9	0.81
43.1.1		Vloerpaneel	Component level	8.00	10%	90%	0%	100%	10	10	0.80	-	1	0.05	0.9	0.86
43.1.2		Stelpootjes	Component level													
41.12.41	41.12.41	BILT_Buitenwandbekleding	Product level	7.00	30%	70%	30%	70%	20	20	2.10	2.10	1	0.30	0.9	0.63
16.1	16.12	Funderingsbalk	Element level	4.00	100%	0%	0%	100%	100	100	4.00	-	1	0.5	0.9	0.45

Appendix 11: Disassembly potential building level 4

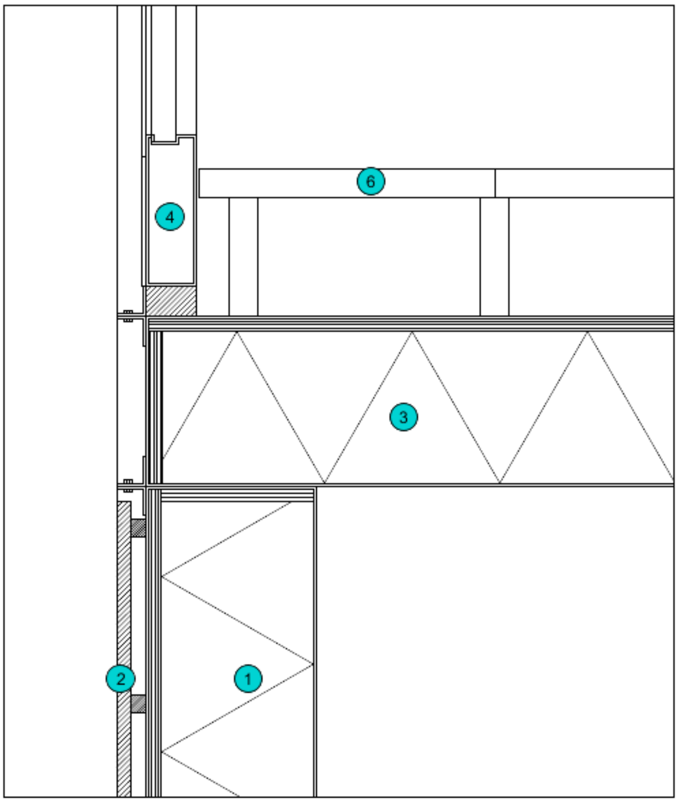
Detail drawing 1 and relational pattern



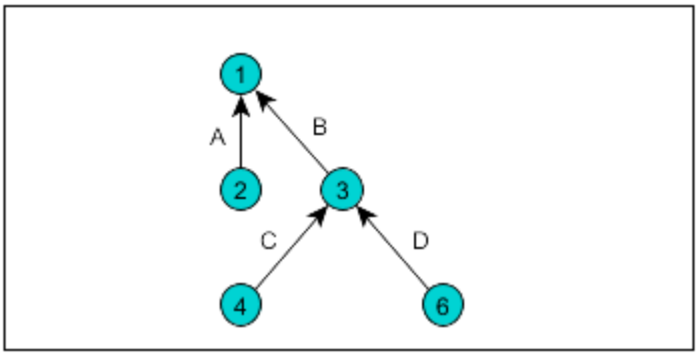
Detail 1



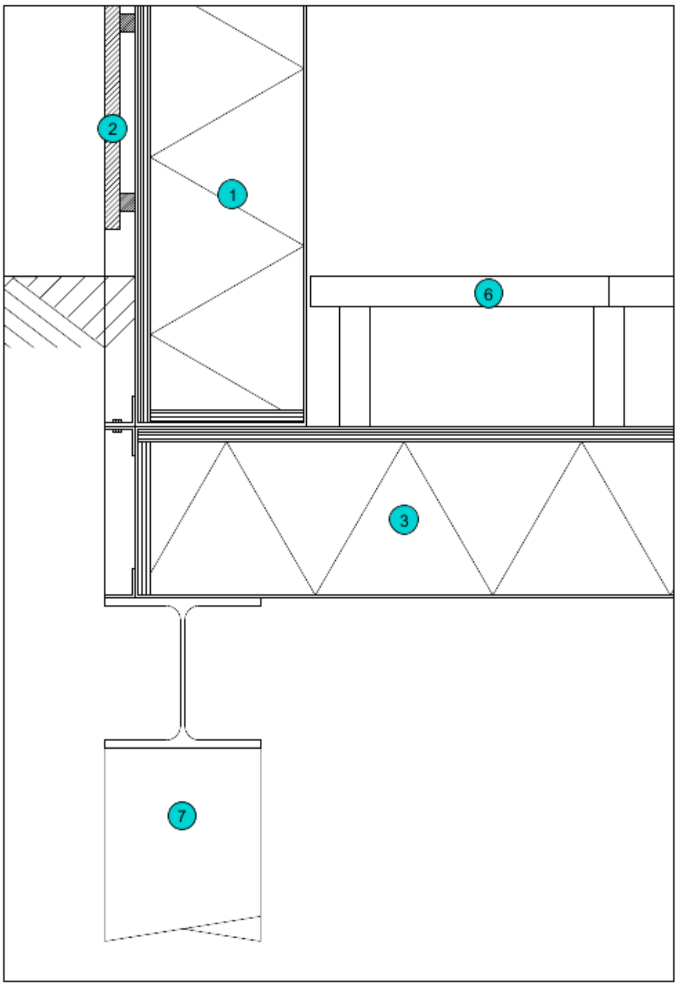
Detail drawing 2 and relational pattern



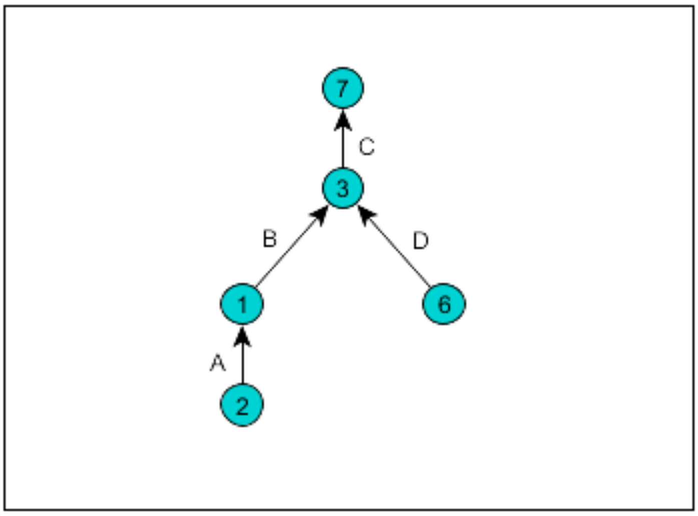
Detail 2



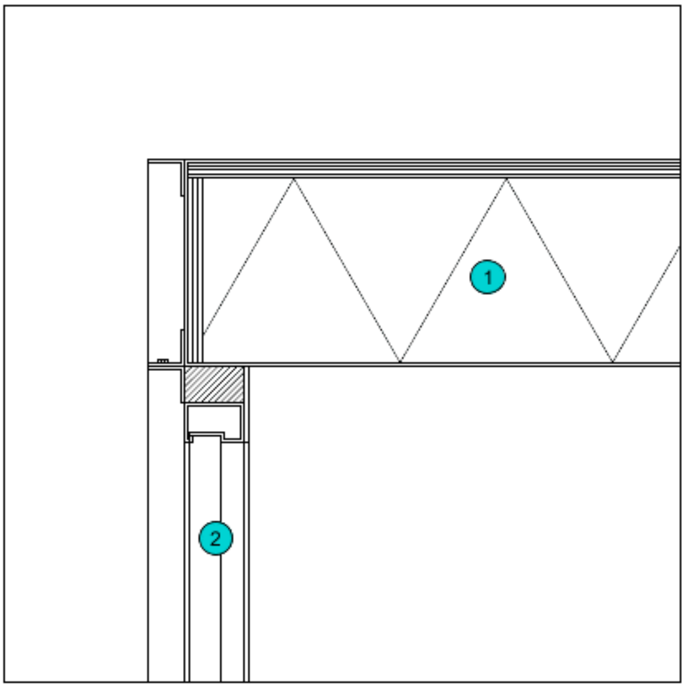
Detail drawing 3 and relational pattern



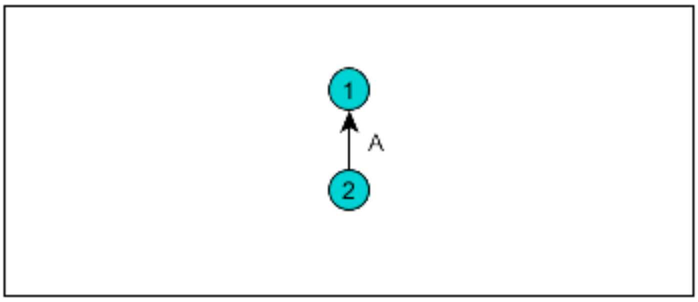
Detail 3



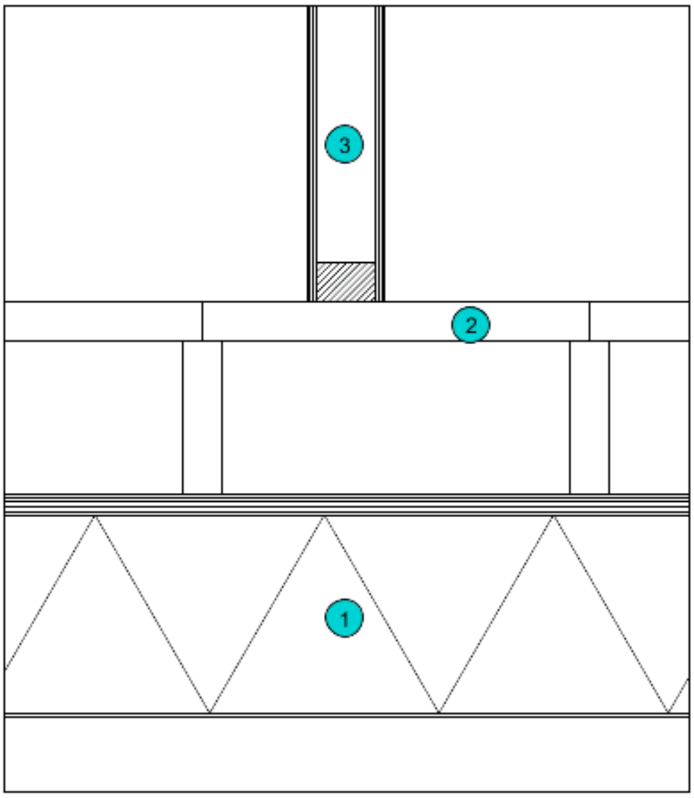
Detail drawing 4 and relational pattern



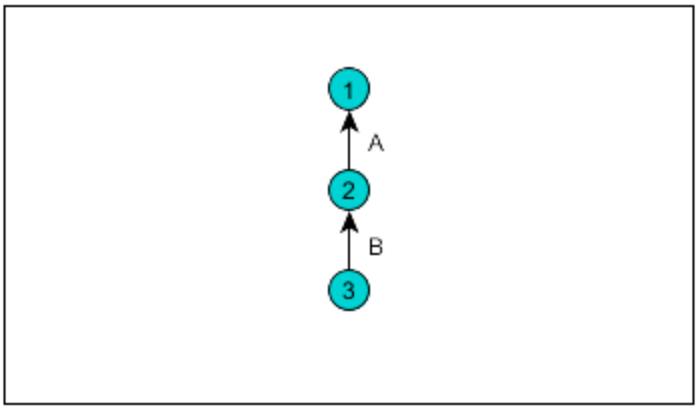
Detail 4



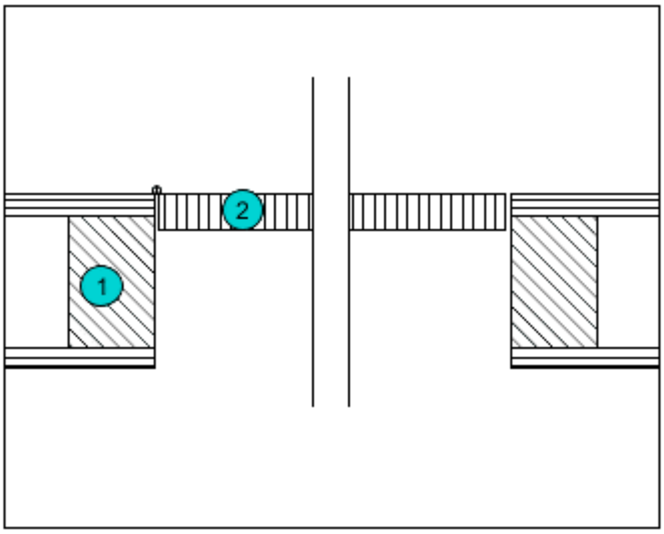
Detail drawing 5 and relational pattern



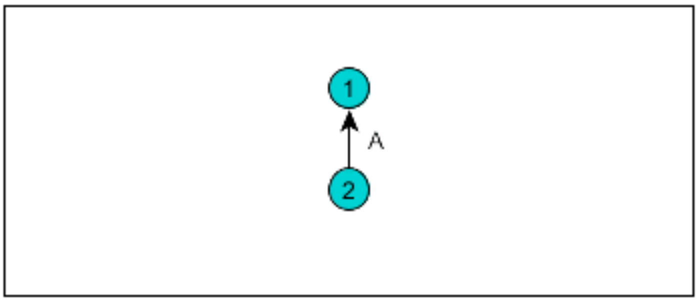
Detail 5



Detail drawing 6 and relational pattern



Detail 6



Assessment of the Product Disassembly Potential

ID	Assembly ID	Node ID	Product description	Product level	Product Disassembly Factors j								Total Product Disassembly Potential
					Assembly shape	PD_j	Independency	PD_j	Method of Fabrication	PD_j	Type of Relational Pattern	PD_j	
21.0300.2760	1	1.1	BILT_wandpaneel	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
41.12.41	1	1.2	BILT_Buitenwandbekleding	Product level	Unsymmetrical overlapping	0,40	Planed for one solution	0,40	Pre-made geometry	1,00	One or two connections	1,00	2,8
23.0300.2400.3	1	1.3	BILT_vloerpanel_dak	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
21.0300.2760	2	2.1	BILT_wandpaneel	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
41.12.41	2	2.2	BILT_Buitenwandbekleding	Product level	Unsymmetrical overlapping	0,40	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	3,4
23.0300.2400.2	2	2.3	BILT_vloerpanel_1e	Product level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,2
31.2.1200.2760	2	2.4	BILT_Kozijnpaneel_1200mm	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
43.12.10	2	2.6	BILT_Verhoogdvloersysteem300x300	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
21.0300.2760	3	3.1	BILT_wandpaneel	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
41.12.41	3	3.2	BILT_Buitenwandbekleding	Product level	Unsymmetrical overlapping	0,40	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	3,4
23.0300.2400.1		3.3	BILT_vloerpanel_BG	Product level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	Three connections	0,60	1,8
43.12.10	3	3.6	BILT_Verhoogdvloersysteem300x300	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
17.11.10	3	3.7	BILT_Schroefpaal	Product level	Insert on one side	0,20	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	3,2
23.0300.2400.3	4	4.1	BILT_vloerpanel_dak	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
21.0300.2760	4	4.2	BILT_wandpaneel	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
23.0300.2400.1	5	5.1	BILT_vloerpanel_BG	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
43.12.10	5	5.2	BILT_Verhoogdvloersysteem300x300	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
22.1200.2600	5	5.3	BILT_Binnenwand_1200mm	Product level	Open linear	1,00	Planed for one solution	0,40	Half standardised geometry	0,50	One or two connections	1,00	2,9
22.1200.2600	6	6.1	BILT_Binnenwand_1200mm	Product level	Open linear	1,00	Modular zoning	1,00	Half standardised geometry	0,50	One or two connections	1,00	3,5
32.31.21	6	6.2	BILT_Binnendeur	Component le	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
23.0300.2400.2	5	5.1	BILT_vloerpanel_1e	Product level	Open linear	1,00	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	3,1
43.12.10	5	5.2	BILT_Verhoogdvloersysteem300x300	Product level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
22.1200.2600	5	5.3	BILT_Binnenwand_1200mm	Product level	Open linear	1,00	Planed for one solution	0,40	Half standardised geometry	0,50	One or two connections	1,00	2,9

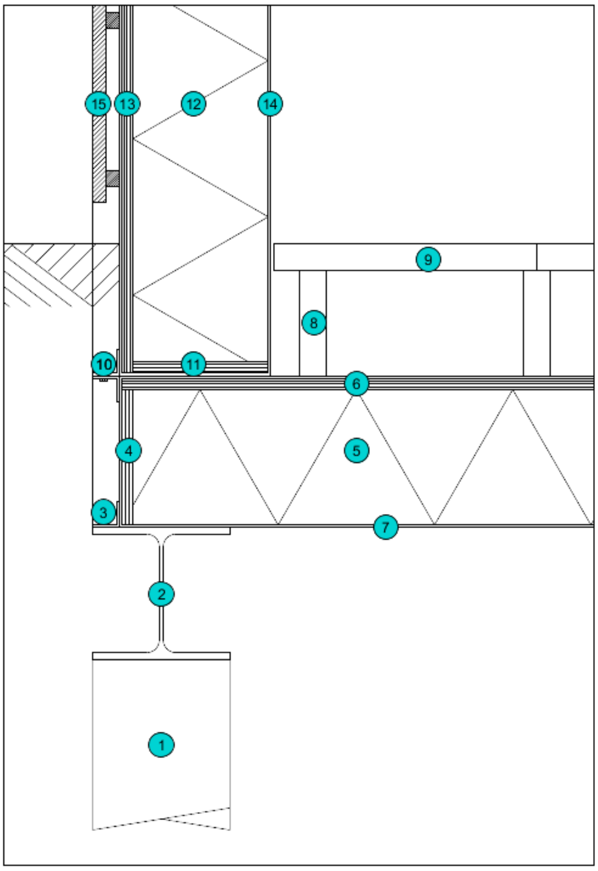
Assessment of the Connection Disassembly Potential

Connection ID	Connection sequence		Connection Disassembly Factors CD_j						Total Connection Disassembly Potential
	Node ID (1)	Node ID (2)	Accessibility to connection	CD_j	Type of connection	CD_j	Assembly Sequence	CD_j	
1A	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
1B	21.0300.2760	23.0300.2400.3	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
1A	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
1B	21.0300.2760	23.0300.2400.3	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
2A	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
2B	21.0300.2760	23.0300.2400.2	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
2A	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
2B	21.0300.2760	23.0300.2400.2	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
2C	23.0300.2400.	31.2.1200.2760	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
2D	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
2C	23.0300.2400.	31.2.1200.2760	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
2D	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
3A	23.0300.2400.	21.0300.2760	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
3B	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
3A	21.0300.2760	41.12.41	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
3B	23.0300.2400.	21.0300.2760	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
3C	17.11.10	23.0300.2400.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
3D	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
3D	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
3C	17.11.10	23.0300.2400.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
4A	21.0300.2760	23.0300.2400.3	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
4A	21.0300.2760	23.0300.2400.3	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
5A	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
5A	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
5B	43.12.10	22.1200.2600	Accessible with additional operation which is reparable damage	0,60	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,7
6A	22.1200.2600	32.31.21	Accessible	1,00	Dry connection	1,00	High level / Low level	0,50	2,5
6A	22.1200.2600	32.31.21	Accessible	1,00	Dry connection	1,00	High level / Low level	0,50	2,5
5A	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
5A	23.0300.2400.	43.12.10	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
5B	43.12.10	22.1200.2600	Accessible with additional operation which is reparable damage	0,60	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,7

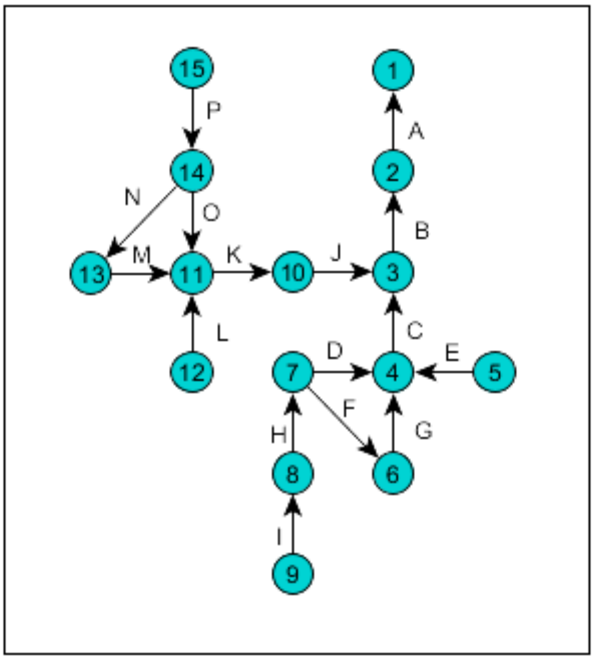
Assessment of the Disassembly Potential

ID	Product description	Product Disassembly Factors j				Total Product Disassembly Potential (PDp)	Disassembly Factors CD_j			Total Connection Disassembly Potential (CD_p)	Disassembly Potential (DP_p)
		PD_j	PD_j	PD_j	PD_j		PD_j	PD_j	PD_j		
21.0300.2760	BILT_wandpaneel	1,00	0,10	1,00	1,00	3,10	0,80	0,80	1,00	2,60	0,81
23.0300.2400.1	BILT_vloerpanel_BG	0,10	0,10	1,00	0,60	1,80	0,80	0,80	1,00	2,60	0,63
23.0300.2400.2	BILT_vloerpanel_1e	0,10	0,10	1,00	1,00	2,20	1,00	0,80	1,00	2,80	0,71
23.0300.2400.3	BILT_vloerpanel_dak	1,00	0,10	1,00	1,00	3,10	1,00	0,80	1,00	2,80	0,84
31.2.1200.2760	BILT_Kozijnpaneel_1200mm	1,00	1,00	1,00	1,00	4,00	1,00	0,80	1,00	2,80	0,97
17.11.10	BILT_Schroefpaal	0,20	1,00	1,00	1,00	3,20	-	-	-	-	-
22.1200.2600	BILT_Binnenwand_1200mm	1,00	0,40	0,50	1,00	2,90	0,60	0,10	1,00	1,70	0,66
32.31.21	BILT_Binnendeur	1,00	1,00	1,00	1,00	4,00	1,00	1,00	0,50	2,50	0,93
43.12.10	BILT_Verhoogdvloersysteem300x300	1,00	1,00	1,00	1,00	4,00	0,80	1,00	1,00	2,80	0,97
41.12.41	BILT_Buitenwandbekleding	0,40	0,40	1,00	1,00	2,80	0,80	0,80	1,00	2,60	0,77

Appendix 12: Disassembly potential building level 5 & 6



Detail 1



Assessment of the Product Disassembly Potential

ID	Assembly ID	Node ID	Product description	Product level	Product Disassembly Factors j								Total Product Disassembly Potential
					Assembly shape	PD_j	Independency	PD_j	Method of Fabrication	PD_j	Type of Relational Pattern	PD_j	
17.1	1	1	BILT_Schroefpaal	Product level	Insert on one side	0,20	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	3,2
16.1	1	2	Funderingsbalk	Element level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
23.1.5	1	3	Extrusieprofiel	Material level	Open linear	1,00	Planned interpenetrating for different solutions (overcapacity)	0,80	Pre-made geometry	1,00	One or two connections	1,00	3,8
23.1.3	1	4	Multiplex tussenschotten	Material level	Insert on two sides	0,1	total dependence	0,1	Pre-made geometry	1	Four connections	0,4	1,6
23.1.4	1	5	Everuse	Component level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,2
23.1.2	1	6	Multiplex schil	Material level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	Three connections	0,60	1,8
23.1.1	1	7	Aluminium schil	Material level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,2
43.1.2	1	8	Stelpootjes	Component level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
43.1.1	1	9	Vloerpaneel	Component level	Open linear	1,00	Modular zoning	1,00	Pre-made geometry	1,00	One or two connections	1,00	4
21.1.5	1	10	Extrusieprofiel	Material level	Open linear	1,00	Planned interpenetrating for different solutions (overcapacity)	0,80	Pre-made geometry	1,00	One or two connections	1,00	3,8
21.1.3	1	11	Multiplex tussenschotten	Material level	Insert on two sides	0,1	total dependence	0,1	Pre-made geometry	1	Four connections	0,40	1,6
													0
21.1.4	1	12	Everuse	Component level	Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,2
21.1.2	1	13	Multiplex schil		Insert on two sides	0,10	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,2
21.1.1	1	14	Aluminium schil	Material level	Overlapping on one side	0,70	total dependence	0,10	Pre-made geometry	1,00	One or two connections	1,00	2,8
41.1	1	15	BILT_Buitenwandbekleding	Product level	Unsymmetrical overlapping	0,40	Modular zoning	1,00	Half standardised geometry	0,50	One or two connections	1,00	2,9

Assessment of the Connection Disassembly Potential

Connection ID	Connection sequence		Connection Disassembly Factors CD_j						Total Connection Disassembly Potential
	Prod ID (1)	Prod ID (2)	Accessibility to connection	CD_j	Type of connection	CD_j	Assembly Sequence	CD_j	
A	17.1	16.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	High level / Low level	0,50	2,1
A	17.1	16.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	High level / Low level	0,50	2,1
B	16.1	23.1.5	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
B	16.1	23.1.5	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,6
C	23.1.5	23.1.3	Accessible with additional operation which cases damage	0,40	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,6
J	23.1.5	21.1.5	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
C	23.1.5	23.1.3	Accessible with additional operation which cases damage	0,40	Filled soft chemical connection	0,20	Same level / Same level	1	1,6
D	23.1.3	23.1.1	not accessible - total damage of elements	0,10	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,2
E	23.1.3	23.1.4	not accessible - total damage of elements	0,10	Dry connection	1,00	Low level / High level	0,10	1,2
G	23.1.3	23.1.2	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
E	23.1.3	23.1.4	not accessible - total damage of elements	0,10	Dry connection	1,00	Low level / High level	0,10	1,2
F	23.1.2	23.1.1	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
G	23.1.3	23.1.2	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
H	23.1.1	43.1.2	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Low level / High level	0,10	1,9
D	23.1.2	23.1.1	not accessible - total damage of elements	0,10	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,2
F	23.1.2	23.1.1	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
H	23.1.1	43.1.2	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Low level / High level	0,10	1,9
I	43.1.2	43.1.1	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
I	43.1.2	43.1.1	Accessible with additional operation which causes no damage	0,80	Dry connection	1,00	Same level / Same level	1,00	2,8
J	23.1.5	21.1.5	Accessible	1,00	Direct connection with additional fixing devices	0,80	Same level / Same level	1,00	2,8
K	21.1.5	21.1.3	Accessible with additional operation which cases damage	0,40	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,6
K	21.1.5	21.1.3	Accessible with additional operation which cases damage	0,40	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,6
L	21.1.3	21.1.4	not accessible - total damage of elements	0,10	Dry connection	1,00	Low level / High level	0,10	1,2
M	21.1.3	21.1.2	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
O	21.1.3	21.1.1	not accessible - total damage of elements	0,10	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,2
L	21.1.3	21.1.4	not accessible - total damage of elements	0,10	Dry connection	1,00	Low level / High level	0,10	1,2
M	21.1.3	21.1.2	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
N	21.1.2	21.1.1	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
N	21.1.2	21.1.1	not accessible - total damage of elements	0,10	Filled soft chemical connection	0,20	Same level / Same level	1,00	1,3
O	21.1.3	21.1.1	not accessible - total damage of elements	0,10	Filled hard chemical connection	0,10	Same level / Same level	1,00	1,2
P	21.1.1	41.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Low level / High level	0,10	1,7
P	21.1.1	41.1	Accessible with additional operation which causes no damage	0,80	Direct connection with additional fixing devices	0,80	Low level / High level	0,10	1,7

Assessment of the Disassembly Potential

ID	Product description	Product Disassemly factors				Total Product Disassembly Potential (PDp)	Connection Disassembly factors			Total Connection Disassembly Potential (CDp)	Disassembly Potential (DPp)
		PDj	PDj	PDj	PDj		PDj	PDj	PDj		
17.1	BILT_Schroefpaal	0,20	1,00	1,00	1,00	3,20	-	-	-	-	-
16.1	Funderingsbalk	1,00	1,00	1,00	1,00	4,00	0,80	0,80	0,50	2,10	0,87
23.1.5	Extrusieprofiel	1,00	0,80	1,00	1,00	3,80	0,80	0,80	1,00	2,60	0,91
23.1.3	Multiplex tussenschotten	0,10	0,10	1,00	0,40	1,60	0,40	0,20	1,00	1,60	0,46
23.1.4	Everuse	0,10	0,10	1,00	1,00	2,20	0,10	1,00	0,10	1,20	0,49
23.1.2	Multiplex schil	0,10	0,10	1,00	0,60	1,80	0,10	0,20	1,00	1,30	0,44
23.1.1	Aluminium schil	0,10	0,10	1,00	1,00	2,20	0,10	0,10	1,00	1,20	0,49
43.1.2	Stelpootjes	1,00	1,00	1,00	1,00	4,00	0,80	1,00	0,10	1,90	0,84
43.1.1	Vloerpaneel	1,00	1,00	1,00	1,00	4,00	0,80	1,00	1,00	2,80	0,97
21.1.5	Extrusieprofiel	1,00	0,80	1,00	1,00	3,80	1,00	0,80	1,00	2,80	0,94
21.1.3	Multiplex tussenschotten	0,10	0,10	1,00	0,40	1,60	0,40	0,20	1,00	1,60	0,46
21.1.4	Everuse	0,10	0,10	1,00	1,00	2,20	0,10	1,00	0,10	1,20	0,49
21.1.2	Multiplex schil	0,10	0,10	1,00	1,00	2,20	0,10	0,20	1,00	1,30	0,50
21.1.1	Aluminium schil	0,70	0,10	1,00	1,00	2,80	0,10	0,10	1,00	1,20	0,57
41.1	BILT_Buitenwandbekleding	0,40	1,00	0,50	1,00	2,90	0,80	0,80	0,10	1,70	0,66

Appendix 13: Comparison new BCI with the old BCI

Result old BCI product level building level 4

Product description	Volume	MCI	Functional separation	Functional dependence	Technical lifecycle	Geometry of product edge	Standardization of product edge	Type of connection	Accessibility to connecti	PCI
BILT_wandpaneel	43.75	0.80	0.60	0.1	1	1	1	0.8	0.8	0.61
BILT_vloerpanel_BG	60.05	0.81	0.60	0.1	1	0.1	1	0.8	0.8	0.51
BILT_vloerpanel_1e	60.05	0.81	0.60	0.1	1	0.1	1	0.8	1	0.53
BILT_vloerpanel_dak	60.05	0.81	0.60	0.1	1	1	1	0.8	1	0.64
BILT_Kozijnpaneel_1200mm	2.00	0.59	1.00	1	1	1	1	0.8	1	0.57
BILT_Schroefpaal		-	1.00	1	1	0.2	1	0	0	
BILT_Binnenwand_1200mm	5.00	0.40	1.00	1	1	1	0.5	0.1	0.6	0.30
BILT_Binnendeur	0.30	0.59	1.00	1	1	1	1	1	1	0.59
BILT_Verhoogdvloersysteem300x300	8.00	0.86	1.00	0.4	1	1	1	1	0.8	0.76
BILT_Buitenwandbekleding	7.00	0.63	1.00	1	1	0.4	1	0.8	0.8	0.54

System	SCI	LK	BCI
Stuff	x		
Space plan	0.58	0.90	
Services	x		
Skin	0.55	0.7	
Structure	0.57	0.2	
Site	x		
Total		1.8	**0.57**

Results old BCI on building level 5 & 6

Product description	Volume	MCI	Functional separation	Functional dependence	Technical lifecycle	Geometry of product edge	Standardization of product edge	Type of connection	Accessibility to connecti	PCI
BILT_Schroefpaal										-
Funderingsbalk	4.00	0.45	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.42
Extrusieprofiel	0.19	0.81	0.60	0.80	1.00	1.00	1.00	0.80	0.80	0.69
Multiplex tussenschotten	1.96	0.45	0.60	0.10	1.00	0.10	1.00	0.20	0.40	0.22
Everuse	48.09	1.00	0.60	0.10	1.00	0.10	1.00	1.00	0.10	0.56
Multiplex schil	9.56	0.45	0.60	0.10	1.00	0.10	1.00	0.20	0.10	0.20
Aluminium schil	0.25	0.81	0.60	0.10	1.00	0.10	1.00	0.10	0.10	0.35
Stelpootjes	1.00	0.86	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.84
Vloerpaneel	8.00	0.43	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.42
Extrusieprofiel	0.21	0.81	0.60	0.80	1.00	1.00	1.00	0.80	1.00	0.72
Multiplex tussenschotten	1.96	0.45	0.60	0.10	1.00	0.10	1.00	0.20	0.40	0.22
Everuse	33.91	1.00	0.60	0.10	1.00	0.10	1.00	1.00	0.10	0.56
Multiplex schil	7.46	0.45	0.60	0.10	1.00	0.10	1.00	0.20	0.10	0.20
Aluminium schil	0.20	0.81	0.60	0.10	1.00	0.70	1.00	0.10	0.10	0.42
BILT_Buitenwandbekleding	7.00	0.63	1.00	1.00	1.00	0.40	0.50	0.80	0.80	0.50

System	SCI	LK	BCI
Stuff	x		
Space plan	0.46	0.90	
Services	x		
Skin	0.50	0.7	
Structure	0.48	0.2	
Site	x		
Total		1.8	**0.48**

Results new BCI on building level 4

Product description	Volume	MCI	Assembly Shape	Independency	Method of Fabrication	Type of Relational Pattern	Accessibility to connection	Type of connection	Assembly Sequence	Disassembly Potential	PCI	PCI * Vol
BILT_wandpaneel	43.75	0.80	1.00	0.10	1.00	1.00	0.80	0.80	1.00	0.81	0.65	28.50
BILT_vloerpanel_BG	60.05	0.81	0.10	0.10	1.00	0.60	0.80	0.80	1.00	0.63	0.51	30.57
BILT_vloerpanel_1e	60.05	0.81	0.10	0.10	1.00	1.00	1.00	0.80	1.00	0.71	0.58	34.74
BILT_vloerpanel_dak	60.05	0.81	1.00	0.10	1.00	1.00	1.00	0.80	1.00	0.84	0.68	41.00
BILT_Kozijnpaneel_1200mm	2.00	0.59	1.00	1.00	1.00	1.00	1.00	0.80	1.00	0.97	0.57	1.15
BILT_Schroefpaal												
BILT_Binnenwand_1200mm	5.00	0.40	1.00	0.40	0.50	1.00	0.60	0.10	1.00	0.66	0.26	1.31
BILT_Binnendeur	0.30	0.59	1.00	1.00	1.00	1.00	1.00	1.00	0.50	0.93	0.55	0.16
BILT_Verhoogdvloersysteem3	8.00	0.86	1.00	1.00	1.00	1.00	0.80	1.00	1.00	0.97	0.84	6.68
BILT_Buitenwandbekleding	7.00	0.63	0.40	0.40	1.00	1.00	0.80	0.80	1.00	0.77	0.49	3.40

Total Volume	246.20
PCI*Volume	147.52
SCI*Volume	0
BCI	**0.60**

Results new BCI on building level 5 & 6

Product description	Volume	MCI	Assembly Shape	Independency	Method of Fabrication	Type of Relational Pattern	Accessibility to connection	Type of connection	Assembly Sequence	Disassembly Potential	PCI	PCI * Vol
BILT_Schroefpaal			0.20	1.00	1.00	1.00	-	-	-		-	
Funderingsbalk	4.00	0.45	1.00	1.00	1.00	1.00	0.80	0.80	0.50	0.87	0.39	1.57
Extrusieprofiel	0.19	0.81	1.00	0.80	1.00	1.00	0.80	0.80	1.00	0.91	0.74	
Multiplex tussenschotten	1.96	0.45	0.10	0.10	1.00	0.40	0.40	0.20	1.00	0.46	0.21	
Everuse	48.09	1.00	0.10	0.10	1.00	1.00	0.10	1.00	0.10	0.49	0.49	
Multiplex schil	9.56	0.45	0.10	0.10	1.00	0.60	0.10	0.20	1.00	0.44	0.20	
Aluminium schil	0.25	0.81	0.10	0.10	1.00	1.00	0.10	0.10	1.00	0.49	0.39	
Stelpootjes	1.00	0.86	1.00	1.00	1.00	1.00	0.80	1.00	0.10	0.84	0.72	0.72
Vloerpaneel	8.00	0.43	1.00	1.00	1.00	1.00	0.80	1.00	1.00	0.97	0.42	3.34
Extrusieprofiel	0.21	0.81	1.00	0.80	1.00	1.00	1.00	0.80	1.00	0.94	0.76	
Multiplex tussenschotten	1.96	0.45	0.10	0.10	1.00	0.40	0.40	0.20	1.00	0.46	0.21	
Everuse	33.91	1.00	0.10	0.10	1.00	1.00	0.10	1.00	0.10	0.49	0.49	
Multiplex schil	7.46	0.45	0.10	0.10	1.00	1.00	0.10	0.20	1.00	0.50	0.23	
Aluminium schil	0.20	0.81	0.70	0.10	1.00	1.00	0.10	0.10	1.00	0.57	0.46	
BILT_Buitenwandbekleding	7.00	0.63	0.40	1.00	0.50	1.00	0.80	0.80	0.10	0.66	0.41	2.90

System Description	Volume	MCI	Assembly Shape	Independency	Method of Fabrication	Type of Relational Pattern	Accessibility to connection	Type of connection	Assembly Sequence	Disassembly potential	SCI	SCI * Vol
System 1	43.75	0.81	1.00	0.10	1.00	1.00	0.80	0.80	1.00	0.81	0.66	28.85457
System 2	60.05	0.80	0.10	0.10	1.00	0.60	0.80	0.80	1.00	0.63	0.50	30.19616

Total Volume	123.80
PCI*Volume	8.53
SCI*Volume	59.0507
BCI	**0.55**