URBAN MINING
IN DESIGN AND CONSTRUCTION PROCESSES

A study on implementing urban mining of existing building elements in the local housing for improving the construction industry towards a circular economy

Niels Franssen

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PREFACE

The circular economy is one of the hottest topics in the current construction industry. In my time as a student at the Delft University of Technology I noticed the growth of the topic circularity within the curriculum, in both the design focused bachelor of the Faculty of Architecture and the Built Environment, but also within the master track Management in the Built Environment. I was privileged to execute a research concerning circularity at Alba Concepts that gave me the opportunity to combine the research field with practice. Even though circularity is developed into a buzzword, my graduation project has reached a state where circularity within the construction sector has been made tangible. As a researcher, I have tried to be a part of the development of the construction industry, to help reaching the Sustainable Development Goals concerning circular economy, determined by the Paris Agreement. With the help of many people, it resulted in this graduation thesis:

Urban mining in design and construction processes; a study on implementing urban mining of existing building elements in the local housing for improving the construction industry towards a circular economy.

After a period of 8 years, my time as a student at the Faculty of Architecture in the Built Environment comes to an end. It has been an amazing journey, a period with incredible experiences and so many people I have met and will stay in touch with in the future. During my bachelors I took a gap year to become the chairman of the board of the study association D.B.S.G. Stylos, what I experienced as one the most important years of my personal development. It made me realize my fascination within the world of architecture is not within designing, but collaborating with people to get projects realized. This was my main reason to start the Management in the Built Environment track. During my master, collaboration and project management kept me interested. This made me decide to finalize my time as a student with a research that could connect me to practice and in addition would give me the opportunity to develop a tool, which potentially could make an impact within the construction industry.

The last year has been a roller-coaster, defined by the many people that I would like to thank for their help. First I would like to thank my graduation supervisors. I would like to thank my first mentor Louis Lousberg for always being helpful, critical and to the point. Because of Louis I was able to start my graduation earlier compared to my fellow students. I would like to thank Alexander Koutamanis for the incredible amount of background information and knowledge in the topics of urban mining and circularity, which always gave me an insight from a different perspective. I would also like to thank Ruud Binnekamp, for helping me developing and construction the operational model, but also for the fun and relaxed discussions that we had at the Civil Engineering Faculty. I could have never completed this thesis without my mentors.

The start of the graduation took place at Royal HaskoningDHV, where I had the possibility to join a pilot of the Joint Interdisciplinary Project (JIP), in which the TU Delft collaborated with external companies from practice. I would like to thank my mentor Koen van Viegen and my fellow students Brian Reinders and Pratul Nema for the development of the research questions. I would like to thank Birgit de Bruin for connecting me to the JIP and Vincent Gruis, Fred Hobma, Hans Hellendoorn and Roberto Cavallo for helping me organizing the JIP in a way it could be implemented within my graduation. I hope I can repay the effort through sharing my experiences with other students.

I would like to thank all my colleagues at Alba Concepts for all the moments they helped me develop my research. Next to the interesting discussions, I was privileged to join many group activities, drinks and events together. I would especially like to thank my main supervisors Jim Teunizen and Jip van Grinsven, next to colleagues Stijn van Enckevort, Sven Bögels and Mike van Vliet, which gave me insight in the practice field of reusable building elements costs and factors. I hope I have repaid their effort by being a useful colleague, for example by giving the new office in ‘s Hertogenbosch a green touch by providing it with all the new plants.

During my graduation, I gained a lot of support from my colleagues at the communication department at the Faculty of Architecture and the Built Environment. I would like to thank Sue van de Giessen, Annet Zorge, Lotte Dijkstra and Nicolet Mansveld-Olsthoorn for always listening to my progress and for providing a personal working spot for me at their office. I would also like to thank Linda van Keeken for her support during this year and Arnout Sabbe for helping me with the collaboration with the Cinderela project.

Finally I would like to thank all my fellow students from Architecture, my soccer team, my neighbours, other friends and my parents for supporting me throughout this project, taking my mind of off the graduation at times as well as helping me remember what is important in life. I especially want to thank Sophie van Bochove for sticking up with me the entire second half of the project, helping me finalizing my master thesis and always being there for me.

My time as a student has come to an end. It has been a wonderful student career and I look forward to what the future will bring me. I hope you will enjoy reading my master thesis.

Niels Franssen
Delft, 05 November 2019

ABSTRACT

In most of the current starting construction projects, most stakeholders use virgin materials for building elements. Considering climate change, building materials are getting scarce, it is necessary to reduce the number of virgin building materials and improve circularity in the construction industry. The problem is the absence of a middle man that could research the data of existing usable materials and connect this information to stakeholders of starting dwelling projects. This raises the research question: How can an operational model link the supply of existing building materials with the demand for new construction projects in order to reduce the use of virgin materials and thereby improve circularity in the construction industry? The goal of this research is to provide a useful tool for the construction industry to join the transition towards a circular economy. Based on three levels of scale, an operational model is developed that gives a comparison between the materials costs of existing building elements and virgin building elements for a starting dwelling project. This comparison results in insight and an overview for clients, such as municipalities or housing corporations into the costs of potential dwellings built with existing building materials. The operational tool also gives insight in whether or not reusable building materials provide a feasible business case, considering a framework based on the clients input.

Keywords

Urban mining, existing building materials, virgin building materials, operational model, project-based, region-based, enterprise-based, feasibility

SUMMARY

I. INTRODUCTION

In the current starting construction projects, most of the materials used for the dwellings are gathered from processing factories. The use of virgin materials is common among regular construction projects and has been used in most of the projects in the past. Considering climate change, building materials are getting scarce (Kleinjan, 2017), it is necessary to reduce the number of virgin building materials and improve circularity in the construction industry. This thesis researches the possibilities of increasing the circularity, by reducing the usage of virgin building materials in construction projects and help the construction industry with the transition towards a circular economy (CE). The building materials that can be gathered by urban mining (UM) must be considered while initiating new projects. The feasibility of the process by adopting reusable materials into the design compared to virgin building elements is also of importance. The market has to be researched, whether or not there is a demand for this type of building materials or this type of system for contractors. It should be researched whether or not it is feasibly possible to adapt reusing materials to make it more cost-efficient, or more interesting according to the Sustainable Development Goals (SDG's) of the United Nations (Davy & Guar, 2018) to receive funding. Creating a business case from the perspective of the middle man should be taken into account as well. This is just a small list of the topics within this research, which in overall tries to clarify the challenges and research how the transition towards a CE could be stimulated in the construction sector.

II. RESEARCH QUESTION

The main objective of this thesis is to support the construction industry with the transition towards a circular economy, by decreasing the usage of virgin building materials. This raises the following main research question:

How can an operational model link the supply of existing building materials with the demand for new construction projects in order to reduce the use of virgin materials and thereby improve circularity in the construction industry?

Figure 0.1 shows a conceptual model of the research at hand. The term UM is supported by the collection of the data. The data arises from the supply that consists of case studies coming from a project-, enterprise- or region-based level context. This supply provides neglected dwellings that

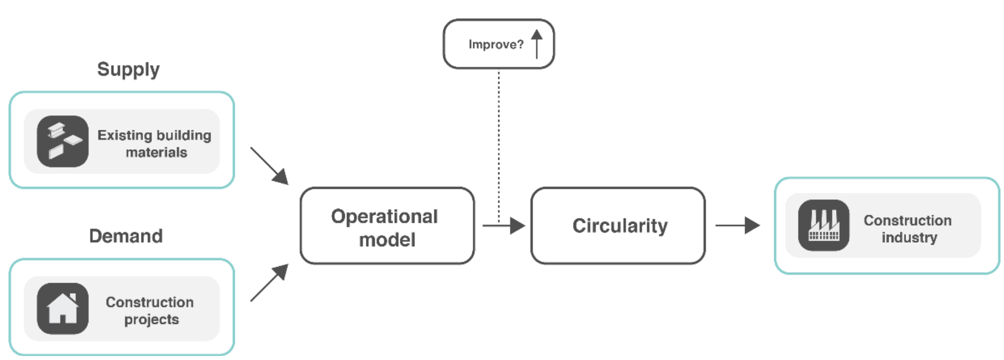

Figure 0.1 Conceptual model research question (own ill.)

consists of building elements. These buildings elements are the reusable materials that trough UM will be used for new construction projects. A comparison of feasibility shows if the circularity of the building sector could be improved.

This conceptual model, combined with the main research question provides the following sub-questions for this thesis:

1. *What specifications are necessary for a case study to be implemented as input for the operational model?*

2. *What is the current demand in the construction industry for new housing projects?*

3. *How can a comparison between the overview of the cost of virgin and existing building elements for new dwellings provide a feasible business opportunity?*

III. METHODOLOGY

Figure 0.2 shows an overview of the setup of the research. This is the starting point of the exploratory research, where the research questions have been developed during the orientating period of the Joint Interdisciplinary Project (JIP). The setup of the research is separated into two different research paths. The left path focussed on the supply side, which consists datasets divided into three levels of scale: project-based, region-based or enterprise-based. The right path of the research setup model focussed on the demand side of the research question that exists of the conducted literature study and expert discussions with stakeholders from practice. It also discovered the correct demand for the program requirements. These two separate paths provided input for the operational model. Eventually, the results of the operational model give feedback to the research questions.

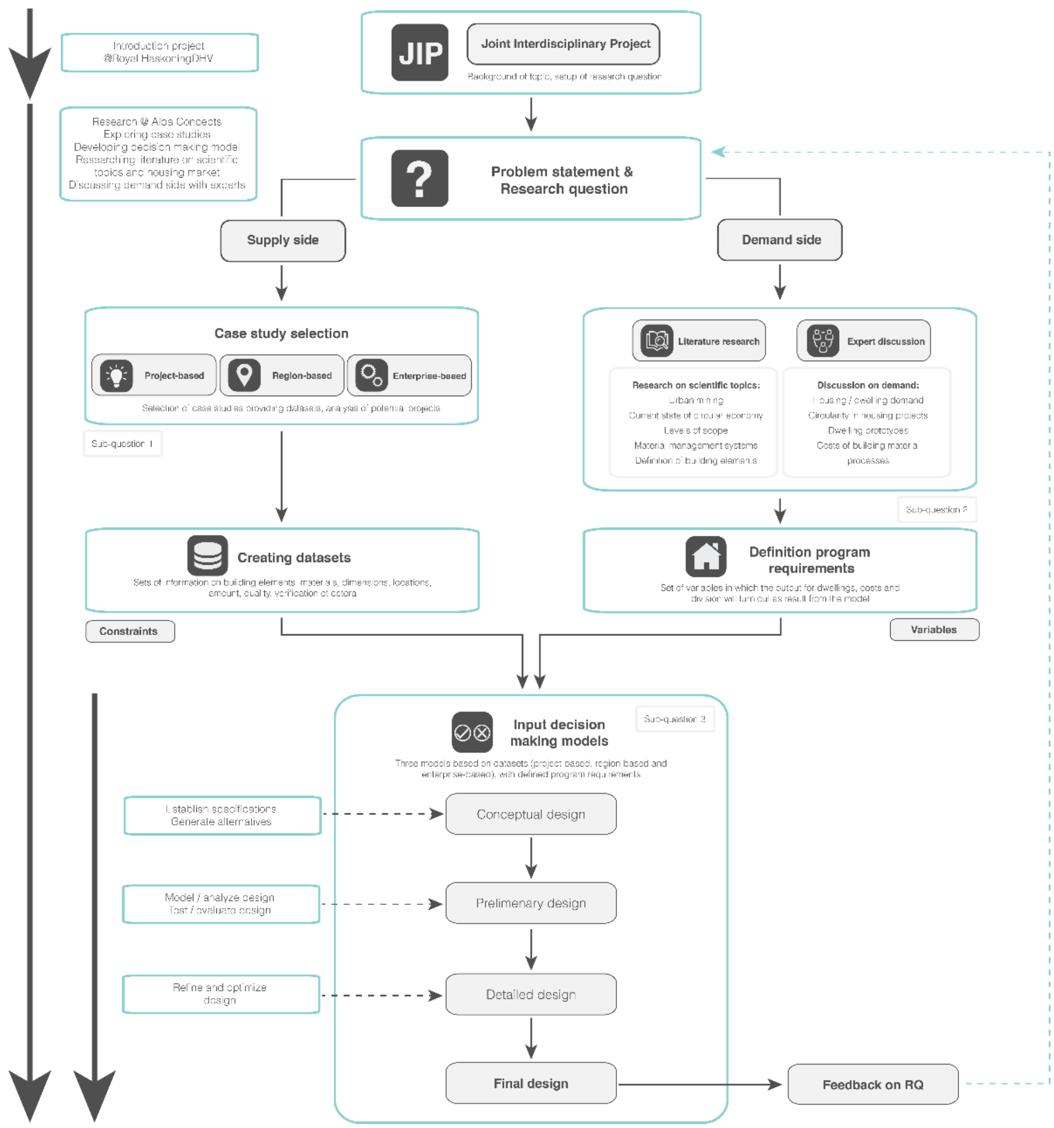

Figure 0.2 Research setup (own ill.)

IV. OPERATIONAL MODEL

Besides the literature research and the expert discussions, a part of this graduation research contains designing an operational model. Operational research deals with operation-related problems, specific research that starts with a typical 'how to' question. It deals with design problems, research about new artefacts that do not yet exist. The goal is to improve a certain subject or topic through designing the operational model and improving the model by running it, again and again, creating a detailed final design (Barendse, Binnekamp, de Graaf, van Gunsteren, & van Loon, 2012). This research provides a model, which uses linear programming to determine what the most optimal solution is, concerning the research goal. Within this research, the model calculates what combinations of dwellings maximizes the use of already available materials, directly minimizing the use of virgin building materials (Binnekamp, 2018). The difference in costs between the dwellings designed with reusable building materials is compared with dwellings built completely with virgin materials. Eventually, this generates results, creating overview and an advice for stakeholders whether or not executing reusing materials will improve the circularity of their project. The model is adaptable to different contexts, by upscaling or downscaling the setup and adjusting the variables and constraints. A schematic overview of the model is presented in Figure 0.3.

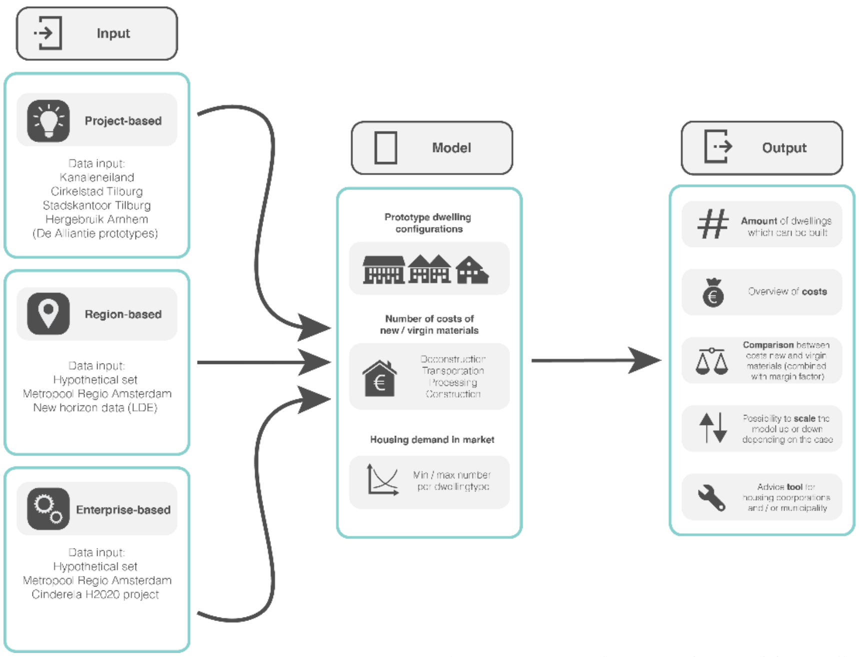

Figure 0.3 Schematic overview decision making model (own ill.)

V. SUPPLY

Datasets from case studies are used as input for the operational model, to determine the supply side of the model and making the connection to real-life problems. The input, consisting of datasets for the model, are provided by multiple different companies. These datasets are divided over the different levels of scale and collected within the schematic overview. The different levels of scale provided the following cases:

- **Project-based:**
  - Bo-Ex apartments Utrecht
  - Project Doen! Stationsarea Arnhem
  - Stadswinkel Tilburg
  - De Alliantie
- **Region-based:**
  - EME-platform
- **Enterprise-based**
  - Cinderela
  - Cirdax / Cirkelstad / New Horizon

The different cases that are researched as input to test hypothetical operational models turned out to be a bit of a struggle. Most of the potential partners lacked corporation, due to privacy regulations. It resulted in a much smaller amount of datasets that were possible to use for the operational model than expected. The consequences were that this research changed the focus towards a realistic output instead of the input. The operational model should be developed in a sense that it is ready to operate, which means that if there are datasets becoming available to use, the model should be designed in a way that data could be directly implemented.

VI. Demand

The Rijksinstituut voor Volksgezondheid en Milieu (2016) stated the challenge that it is important to design buildings in such way that all of the materials in them are suitable for high-quality reuse. However, the long life of building structures – 50 to 100 years – makes it difficult to determine how the materials will be dealt with in several decades' time. So it makes sense to analyse the current standard dwellings and determine which materials have the potential to be reused. This will be input for the operational model.

The RVO (Rijksdienst voor Ondernemend Nederland) provided, in collaboration with Royal HaskoningDHV, six different types of standardized dwellings that nationwide can be used as reference dwellings. These documents exist of all the practical information about the dwellings. Within these six types of standardized dwellings, three have been chosen to be analysed, which are the standard row-house, the semi-detached dwelling and the completely detached dwelling. The dwellings are analysed on a set of topics related to the materials used within the building, which are of use to determine the right quantities of materials which have the possibility to be reused within the dwellings. Dwellings contain multiple building materials and elements, but not every element is fit for reuse. There are certain factors that determine whether or not materials could have a second life cycle that directly reacts to the detachability of building materials, which influences the quality of the material when it is detached or wrecked. The factors that decide how much materials are being influenced by accessibility of connection, detachability of connection and other specifications for materials are designed by Durmisevic (2006).

A set of six different types of materials show the highest possibility of reusability. The choice on these six types of materials is based on an analysis of the present building materials in dwellings in collaboration with a colleague of Alba Concepts. The type of materials that are used for the elements within the dwellings are based on existing details, which are based on the 'SBR-Referentiedetails' for dwellings (Nieman, 2015). These details consist of exact information on what type of material is used for every particular part of every element, which directly connects to the following six different materials:

- **Floors:** Channel plate floor on the ground level (150mm thickness) and the first or second level (200mm thickness);
- **Exterior wall:** Prefab concrete walls (Residential partitioning wall) and Clickbricks (Façade);
- **Interior wall:** Prefab panels (Ytong or Faay panels);
- **Roof:** Ceramic roof tiles;
- **Doors:** Corridor doors, Façade doors (front) and French door (garden);
- **Windows:** Meranti frame.

VII. Feasibility

The clients that are interested in reusing building elements should have a clear view on the cost overview of virgin and reusable materials. This comparison gives insight whether or not using reusable building materials is a feasible business case. Figure 0.4 shows the entire overview of the investment costs for a construction project (Gemeente Amsterdam et al., 2017). In this research, the calculation focusses only on the material costs of the MAMO overview (MAMO: Materiaal, Arbeid, Materieel en Onder aanneming).

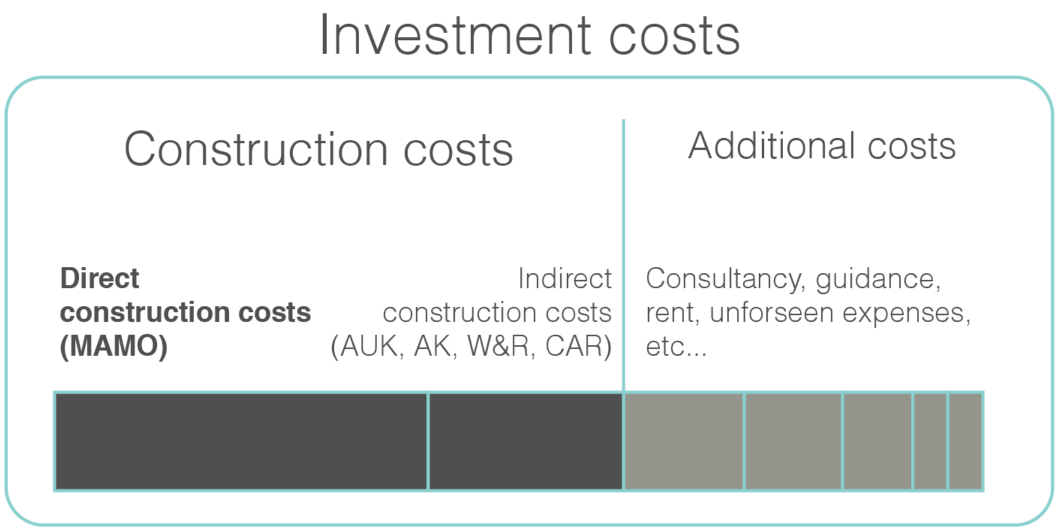

Figure 0.4 Investment costs of a construction project (Gemeente Amsterdam et al., 2017)

The virgin building material costs are determined, based on practice and prices used by contractors in current traditional projects. Next, based on input generated from the current innovation on circular economy of the construction industry and discussion sessions with experts, a substantiated calculation on the costs of reused building materials is presented. This is shown in Figure 0.5. The costs for reusable materials per square meters [€/m²] consists of the sum of the deconstruction factor, the transportation factor and the material validation factors, which are the external influences multiplied by the life span and the LI (losmaakbaarheidsindex), developed by Alba Concepts.
An important notice is that this formula is based on the assumption and interpretation of different factors, which are coming from experts that are active in the field of circular construction industry, but the formulas haven't been applied to cases yet. Every single part of the calculation should be tested and substantiated before the formula can be applied in practice. When it is eventually being used, the test cases show which factors have the most influence in the outcome of the costs, also directly putting the reliability of this factor in perspective.

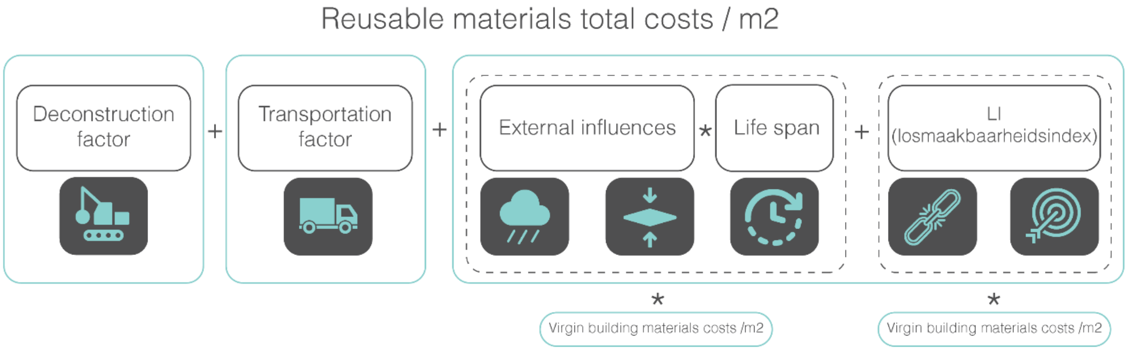

Figure 0.5 Reusable materials total [€/m²] (own ill.)

VIII. Results

The gathering of information on the supply and demand side of the research setup resulted in the execution of a hypothetical project-based model, which generates the output of an example operational model. The results consists of the following subjects:

- Reused building materials.
- Reference dwellings to be built.
- Financial comparison between reused and virgin building materials.

The results of the comparison of costs in the project-based model are visible in Table 0.1 . The table shows that, based on the number of reusable materials available, the three dwelling types as reference, the distance of the sources of the materials, the budget and the demand of dwellings by the client, it would be 14% cheaper to use reusable building materials compared to virgin building materials. However, a lot of different assumptions are made to achieve this result and the framework used for the operational model creates a large number of interesting topics for discussion.

IX. Discussion

The results of the project-based level calculation show that it is, in fact, cheaper to use reusable materials for new dwellings to develop. But, there are many factors that should be taken into consideration when stating the fact that reusable building materials are cheaper than virgin materials. The construction industry is far more complex than the costs for just the building materials. To transform the entire structure of the construction industry, far more extensive research should take place and even when it is researched, due to the large scale and the many stakeholders within the construction industry, it would take years, even decades to transform the system. However, for this research, certain assumptions made within the scope of the reuse of building materials are discussed. Four main topics of discussion are provided, each related to the scope of the research and substantiated with arguments to take into account when stating the results mentioned in the former chapter.

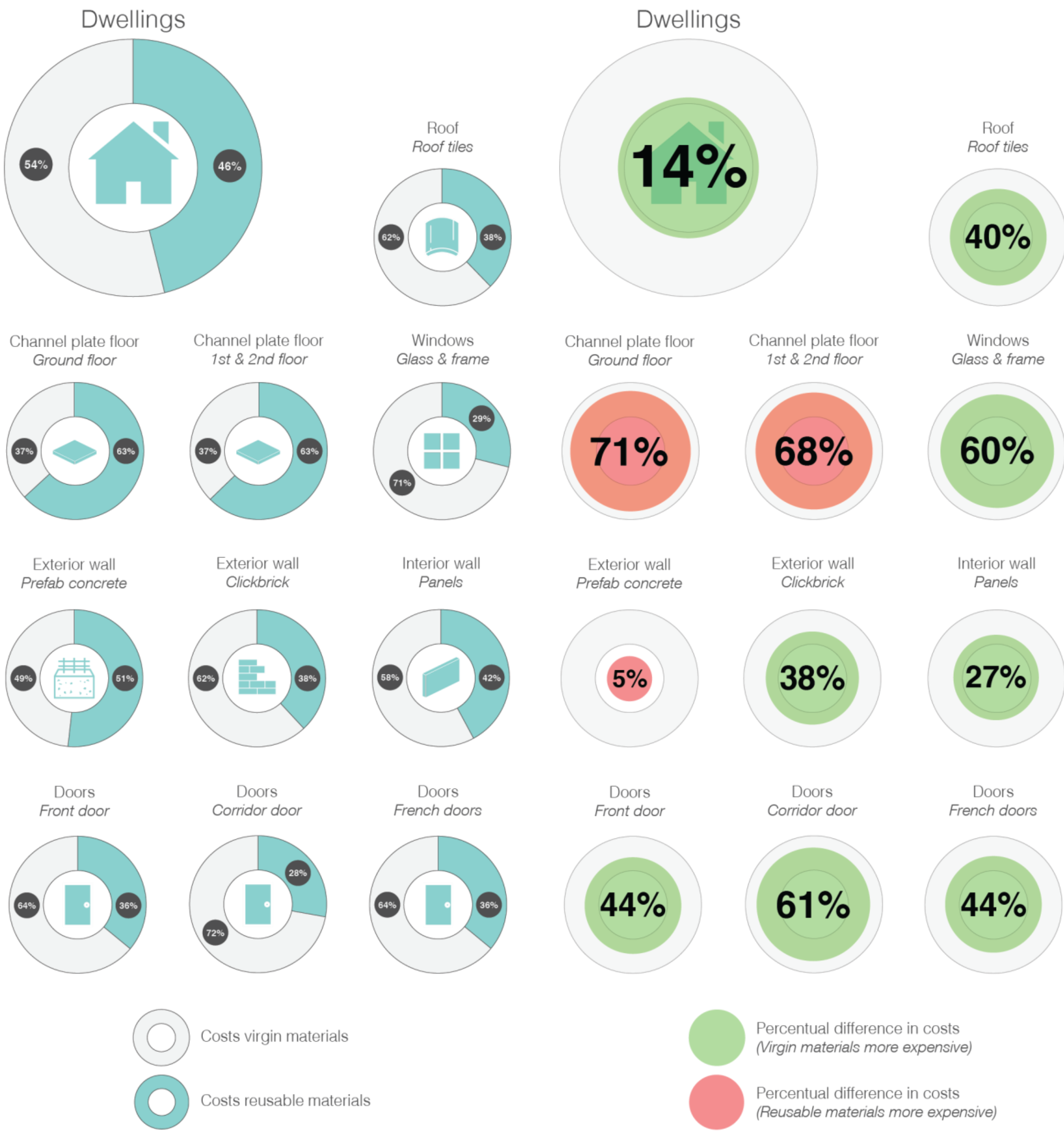

Table 0.1 Project-based model output (own table)

There is a lack of transparency in the availability of reusable building materials. Even though there is so much material out there, ready to be reused, there is no clear overview of what the exact numbers, dimensions, quality and other specifications are. The problem is the competition between the different suppliers, which creates a barrier between demand and supply. The irony is that multiple organisations who are leaders in this transition are all about collaborating, sharing, transparency and other motivational speeches, but in reality, the construction industry is far from an integrated collaborating structure.

Figure 0.6 Discussion topics (own ill.)

The second topic of discussion is related to the actual materials that will be reused. The six types of building elements are divided into a set of materials which show potential to be reused or related to reference projects that showed whether or not the material could be reused. However, the number of materials are chosen within a certain scope, while in fact much more of the building elements of dwellings should be reused. In this research, the final calculation shows the comparison between the costs of the reusable and virgin building materials, which can be reused. However, for an entire dwelling to be realized, much more materials are necessary. Looking at the layers of Brand (1994), the other layers, such as 'services', 'space plan' and 'stuff' are not taken into account in this calculation. If more information and techniques are used to deconstruct and preserve the other building elements, the list of to be used materials will be larger, thus creating more dwellings with almost completely reused materials.

To calculate an entire project of creating dwellings with reused building materials, much more aspects of costs should be taken into account to create a complete, well-substantiated comparison of costs and the entire budget. Also, the virgin material costs overview is based on sources online, but these source of costs is different for each material. The formula designed for reusable materials is probably the most interesting point of discussion. This calculation is not yet being used in practice and is an interpretation of different investigations of commodity valuations and factors of detachability and deconstruction. To actually validate the formulas, real-life projects with correct input are necessary to see if it would generate a realistic outcome.

Projects such as dwellings constructed with reusable structural materials will never take off unless there is a significant amount of stakeholders involved within the process. If the initiative comes from a municipal department, partners in the possession of datasets of building materials are necessary, but also companies who are willing to take on construction projects with reusable materials. Without multiple stakeholders with ambitions for circularity who join the project during the initiative phase, the goals set to be achieved will be harder to reach.

X. Conclusion

The main research question of this research is:

How can an operational model link the supply of existing building materials with the demand for new construction projects in order to reduce the use of virgin materials and thereby improve circularity in the construction industry?

The main conclusion:

*By developing an operational model which calculates the **difference in costs** between the reused and virgin building materials, showing that the reusable materials are **cheaper** compared to the virgin materials, based on the given **framework**.*

This question generated the research goal of reducing the usage of virgin building materials in starting construction projects. Looking at the results of the project-based level operational model, it shows in the comparison in feasibility that the costs for reusable materials are cheaper compared to the virgin building materials. This resulted in an overview and insight for the hypothetical client of the project, which shows it is more interesting to invest in reusable materials compared to virgin materials. This could lead to a reduction in the usage of virgin building materials, which was the goal of the main research. Also, the final deliverable, which is the operational model, proves its functionality and showed insight within the solution space. It is developed with the possibility to implement different datasets, multiple variables and other factors. The qualities that the operational model presents show the value of the model for the construction industry.

With presenting this conclusion, a set of comments should be made to substantiate the statement listed above and the quality's that are related to the operational model. In the discussion chapter, the framework in which the results were executed is based on a set of assumptions that lead to a positive outcome of the comparison. This means that every context leads to a different result, so the numbers presented are purely to provide insight for companies or municipalities who would consider reusing building materials. To execute the project, much more research and additional variables are necessary to create a closed framework with a realistic outcome.

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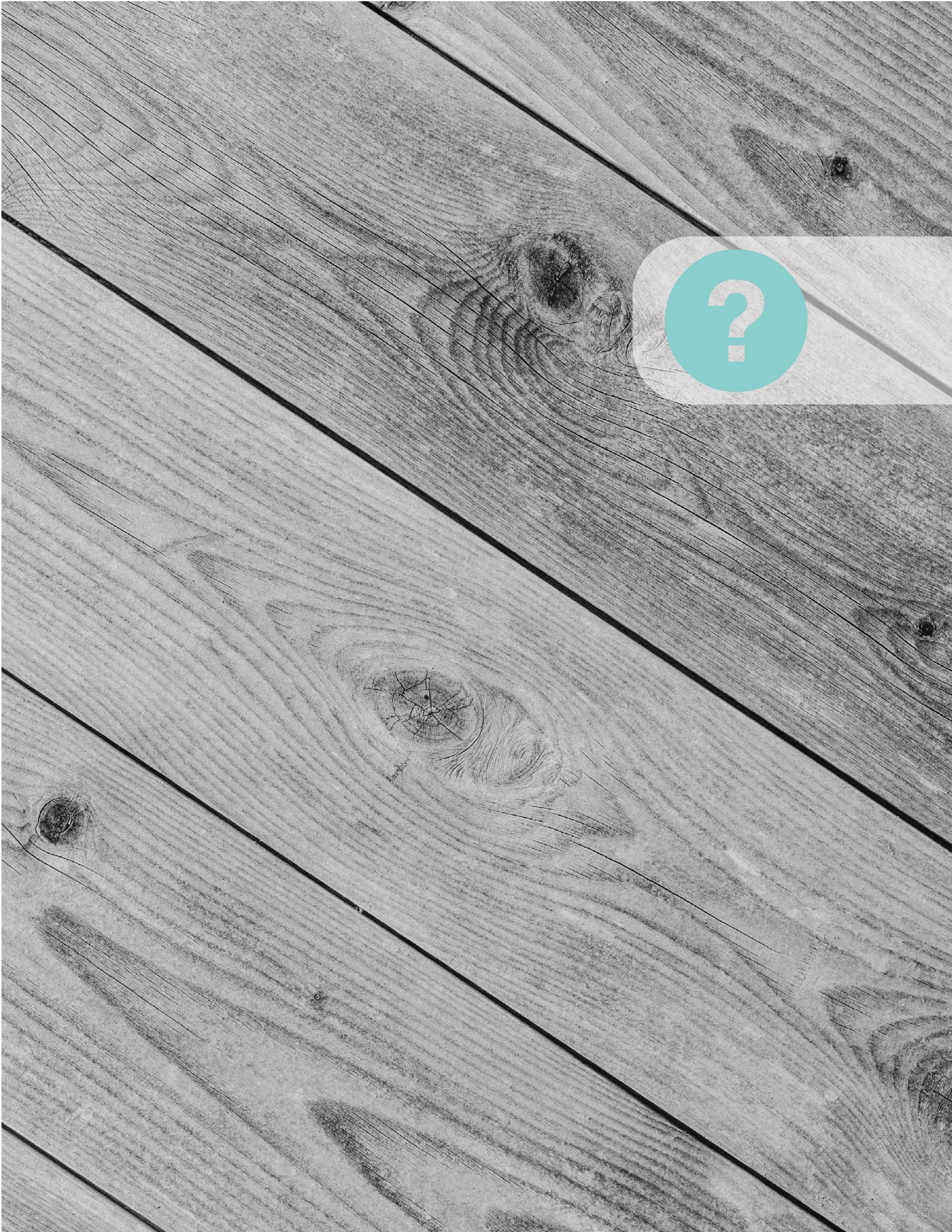


PART 1 INTRODUCTION

The research presented in the following paper focusses on one of the most current topics within the construction industry. The term circularity and circular economy are trending and most of the starting construction projects take action to provide a connection with circular goals. This research tries to contribute further development of the construction industry, concerning the transition towards the circular economy. For this transition to happen, the entire structure of the construction industry has to be taken into account. The large amount of different processes makes it difficult to stimulate a transition for the entire industry. This research focusses on the specific part of the construction industry which has the potential to be re-organised, concerning the usage building materials for new construction projects. The usage of reusable building materials is not implemented yet in the traditional construction sector, due to lack of overview of information and the possibilities for implanting reusable materials. There is a missing link between information and most of the stakeholders which are active in the construction industry. By comparing the costs of virgin building materials to the reusable building materials for new construction projects, this research will try to provide insight and an overview of the possibilities for the stakeholders, promoting to reduce the usage of virgin building materials in future construction projects.

The structure of the report consists of four main chapters, starting with the introduction that presents the research by displaying background information of the main subject and the problem statement, which formulates the research questions. Following is the literature research to substantiate the research topics. In the third chapter, the methodology is explained. The research design is elaborated and the different models that are developed within the research are explained and discussed. The demands and variables of the final objectives are presented, the setup of the operational model is introduced and the input for the operational model is elaborated. The fourth chapter introduces the main findings, analyses the model and reacts to the research questions of the first chapter. The report is discussed and concluded in the fifth and the sixth chapter, reflecting on the introduction and recommending on to further developments within the field.

1.1 RESEARCH BACKGROUND

This chapter presents the background of the research, following by the problem statement. It shows the main topics of the research, concerning the construction industry, the circular economy, the case of Groningen and the energy transition. The introduction sets up a framework on which the problem statement and research questions are developed.

1.1.1 THE CURRENT STATE OF THE BUILDING SECTOR

In the building sector and environment, every active stakeholder notices there is a transition starting from linear to circular. Current trends show that there are many developments concerning sustainability taking place in multiple sectors, to create a circular economy (CE) in the Netherlands by 2050 (Rijksoverheid, 2016a). Digitalization is becoming more and more important, providing innovation, smart business models and artificial intelligence (Kurzawska, 2018). The building sector needs to take action as well and is lacking to join the innovation, even though the building sector is growing in size at unprecedented rates and it will continue to do so over the next 40 years (UN Environment and International Energy Agency, 2017). With all these future projects predicted to be down cycled, the current methods of the construction industry should be taken into consideration. At the moment, more than 90% of the world's construction projects are either over time or over budget (Flyvbjerg, 2014). With innovation in the construction industry, the number of projects being over time or over budget could be downgraded. If building methods could develop into more efficient and sustainable methods, the efficiency and circularity of the sector could grow, effectively completing more projects in time and on budget.

In most of the traditional starting design and construction housing projects, most stakeholders use virgin materials for building elements and to design and construct new dwellings. Recycling and downgrading are techniques that are already incorporated at such level, but the complete reuse of building elements and building materials could be increased. The question stakeholders should ask themselves: Is using virgin materials the most feasible option? There are a lot of building materials available in different artefacts which existences is unknown for interested stakeholders. For example, large construction and demolition companies produce a lot of waste. This is being recycled on a large scale for e.g. roads. However, building materials are hardly ever reused in the construction of new buildings (RIVM, 2016). If the reuse of building materials will be increased, it decreases the production of virgin building materials, which means that less building waste and processing system are necessary. Buildings and roads do account for an estimated 60% of the total materials used

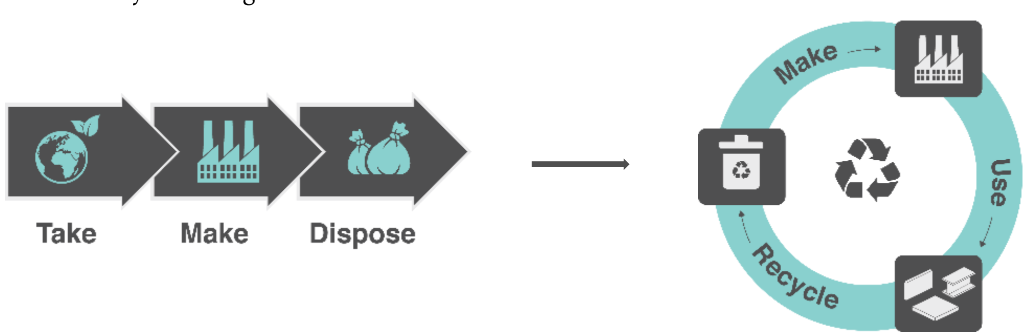


Figure 1.1 Combined overview of transition LE to CE models (own ill.)

globally (Black, 2018) so if only a part of the materials could be collected from another source instead of virgin produced materials, it would save a huge amount of materials being down cycled to a less valuable product after demolition. This would create a reduction of materials to be down cycled, incinerated or send down to landfill, resulting in fewer volumes of waste coming from the construction industry, an improvement for the CE. Eventually, the goal for the building sector in the Netherlands towards a CE is to create more circular processes, instead of linear processes (Figure 1.1). This research focusses on the transition of this process, with the goal to reduce the virgin building materials in starting design and construction process and to make the Dutch building sector join the transition towards a CE step by step.

1.1.2 CIRCULAR ECONOMY

The gap between the knowledge of available materials and the direct implementation of these materials within new projects is the challenge to face. This research reviews the possibilities of closing this gap and providing a useful tool for the construction industry to join the transition towards a CE. The term circular economy (CE) is used in multiple sectors. In the building sector CE is defined as an economic system focused on maximizing the use and reuse of products and raw materials and minimizing value destruction (RIVM, 2016). The CE is a current trend in multiple sectors. The need for a CE is coming from the Sustainable Development Goals, which are highlighted in section 1.1.5. Following the Sustainable Development Goals by the United Nations, the government of the Netherlands decided on three reasons why we need to switch towards a CE: (1) the increasing demand for raw materials, (2) dependence on other countries and (3) the impact on the earth's climate (decrease of CO_2 emissions). Moving towards a CE also offers opportunities for businesses (Rijksoverheid, n.d.-b). Although, what do we exactly mean by CE? Many different researchers made an attempt to figure out the right description for the term, but because of the broad perspective and multiple fields the term is mentioned in, it is impossible to determine the one correct description for the term, that makes it such an interesting and hot topic. For example the RIVM (2016) describes the CE as an economic system that focusses on maximizing the use and reuse of product and raw materials and minimizing value destruction. While van Hemmen (2016) states that the CE is a state of the global economy that is capable of continuous recursion. This implies infinite material productivity regarding non-regenerative materials, which intends recursive recovery of wastes and an absence of resource extraction. The focus on the CE as a regenerative system is mentioned multiple times. For example Geissdoerfer, Savaget, Bocken, and Hultink (2017) define the CE a to be regenerative, a system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops, while EMF (2017) based the transition towards a CE on three principles: Design out waste and pollution, keep products and materials in use and regenerate natural systems. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. To achieve the transition, a redesign of the current economic system is suggested, largely based on linear resource flows, towards closed-loop resource flows that can preserve the embedded environmental and economic value in resources for as long as possible (Nußholz, 2018). The closed loop system which the CE proposes is also mentioned by EMF (2016), where products and services are traded in close loops or cycles.

It is noticeable that most of the literature provide definitions are mostly similar to each other. Reducing waste and creating loops are essential in a CE, to create as less value destruction of the materials as possible. The system should be transform into a regenerative system. The entire economy should be designed in a sense it could adapt the reusability of products and elements. This is comparable to the goals of the construction industry, creating design and construction projects, keeping the factor of reusability of the building elements in mind. Only when there is an integrated system or loop, the effects of a CE can actually benefit society. Multiple literature studies also propose the way material flows should be managed to achieve the change, in order to maintain and restore the materials throughout material banks. This sheds new light on the value of the building materials and products (R. J. Geldermans, 2016). In the research question and the problem statement chapter, it is explained how the CE relates to the main research question of this thesis.

1.1.3 JOINT INTERDISCIPLINARY PROJECT

A graduation research at the Technical University of Delft, especially at the Faculty of Architecture and the Built Environment, consists of a time period of approximately one year. The first period of this graduation research started with a separate project. This Joint Interdisciplinary Project (JIP) was initiated by a collaboration between Royal HaskoningDHV and the Technical University of Delft. The project team consisted of three students from different faculties of the TU Delft, guided by a mentor from the company Royal HaskoningDHV. The end results of the JIP were presented to multiple other teams with different assignments, presenting and collaborating together. Also, the progress for the graduation thesis, developed during the JIP, was presented at the same moment in time, as the P1 presentation. The structure of the JIP consisted of a joint product goal during the 10 weeks of the internship and personal research for the graduation proposal that continued when the internship was finished. The data and knowledge gathered during the internship support the further graduation thesis. The internship provided documents and data about existing dwellings in Groningen to use during the research and as a test case. During the internship, the setup of the main research question and sub-questions of the graduation project were formulated.

The JIP team consisted of the following students and mentor:

- **Brian Reinders** Student Mechanical Engineering, Faculty of Mechanical, Maritime and Materials Engineering
- **Pratul Nema** Student Construction Management and Engineering, Faculty of Civil Engineering and Geosciences
- **Niels Franssen** Student Management in the Built Environment, Faculty of Architecture and the Built Environment
- **Koen van Viegen** Company coach and mentor, a structural engineer at Royal HaskoningDHV

The case of the JIP was focused on the northern province of the Netherlands, Groningen. The Northeast part has been experiencing increased seismic activity in the recent past. This change in seismic behaviour has been attributed the gas extraction in the area. Although natural gas extraction has come to an end, the risk of a possible earthquake remains. Many of the existing buildings require to be reinforced to ensure that they can continue to be used. This reinforcement needs to be able to handle an earthquake with a magnitude of 5 on the Richter scale without showing any significant damage. Since the beginning of gas extraction by drilling activities of oil companies such as Shell and Exxon, over 1500 earthquakes have taken place in the province of Groningen (Dwarshuis, 2018). The largest earthquake since a period of over 5 years took place on the 8th of January 2018, in the village Zeerijp. It was measured at 3,4 on the Richter scale (Leijten, 2018). Approximately 104 buildings in the province of Groningen have been destroyed by earthquakes caused by the gas extraction and 607 buildings are on the shortlist of endangered buildings (Haije, Schüren, van Sluis, & Wind, 2018). Most of the buildings are masonry structures, which led to unavoidable damage like cracks. In a certain situation, it could make more sense to rebuild the house, instead of renovating the old building. The materials of the current housing used for the rehabilitation should be recycled, reclaimed or sourced locally instead of dumping the remains. This could be achieved with a large amount of data about each of the buildings and recover the materials by urban mining.

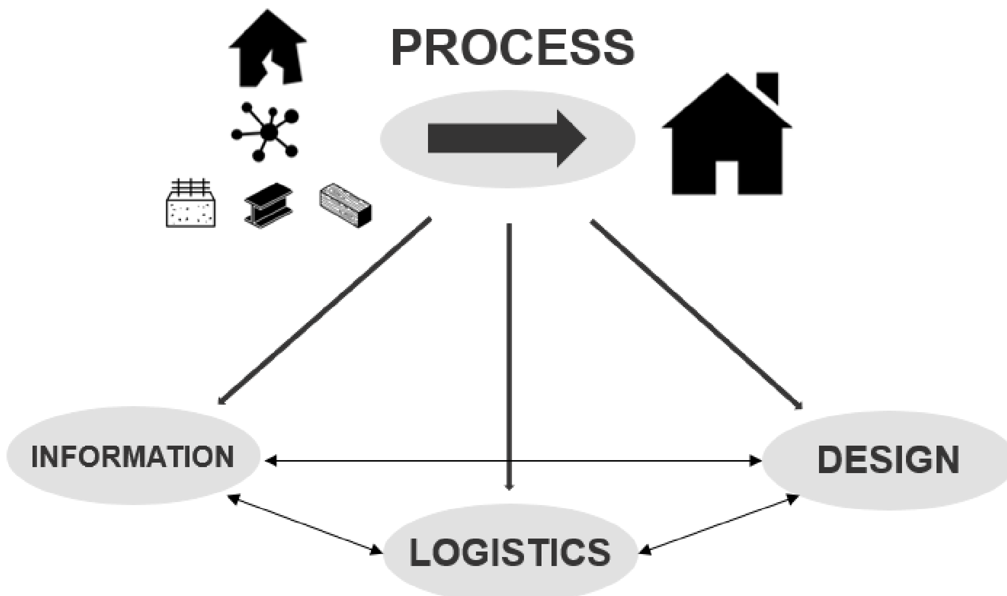


Figure 1.2 Division of elements within design process tool (Franssen et al., 2018)

The datasets which are available within Groningen, collected by Royal HaskoningDHV, made the case interesting to use as a test for this graduation research. Together with the 2 other students, a division was designed to focus on during the process of developing the tool. These three elements were (1) information, (2) logistics, and (3) design (Figure 1.2). Each student was responsible for the development of an element. The data of the dwellings collected by Royal HaskoningDHV had to be managed. The building information of the projects is analysed and the different data files were handled in programs such as Python. These types of programming language could extract datasets from IFC and JSON files, to create accessibility of the information which are stored in public databases. The building information became understandable and ready to apply within the research. The logistic element focused on an efficient operation on the transportation of materials, based on theoretical background concerning several logistic models. To create the transportation system some routing theory has been used to figure out the best possible routing for minimum travel distance, that eventually created a discrete event model to simulate the situation (Franssen et al., 2018).

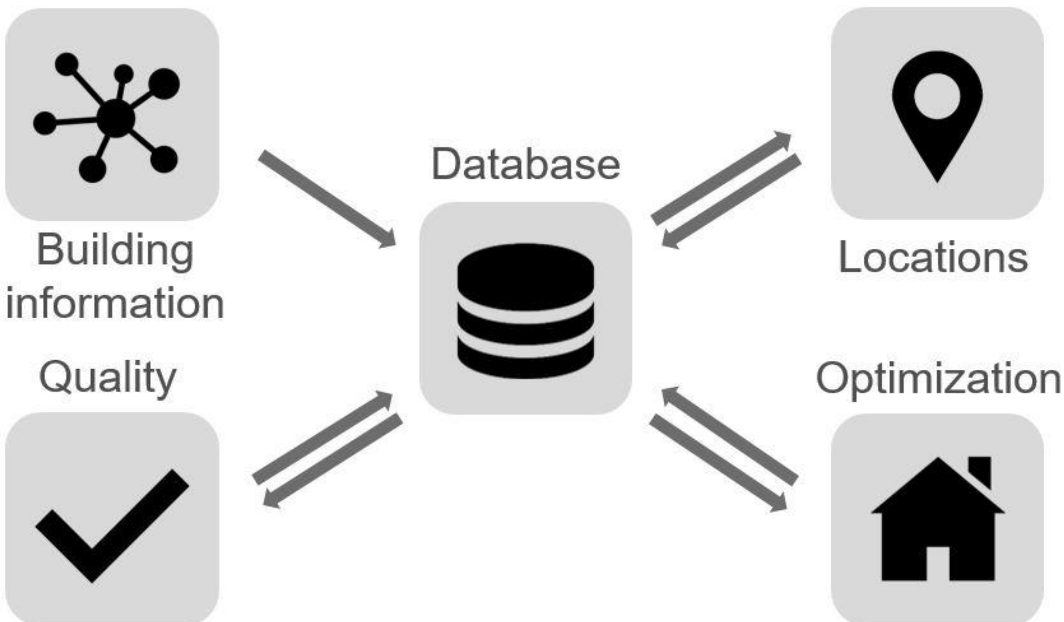


Figure 1.3 Urban Mining Data Management Tool (Franssen, Nema Nagendra Kumar, & Reinders, 2018)

These elements provided the Urban Mining Data Management Tool (Figure 1.3). This tool creates a potential use for the building materials into new housing projects. The model uses one single database, created by the programming methods. This database has all the information and processes that are used to complete the stored products. From the beginning to the end, it is possible to input data. As a result, a design advice has been created. This is the function of the third element. Upcoming housing projects that could be initiated by the client, in this case, the municipality of Groningen, could use this data management tool to directly use the data of the existing buildings in their area and input preferences on their quantities, locations and dwelling types (Franssen et al., 2018).

The tool is a conceptual setup of what could be a working model. It is an interdisciplinary connected tool that could and should be extended with multiple data and tools, but within the possible time frame, we made it possible to create the tool so it can be used in a conceptual manner. Figure 1.4 shows which parts the data goes through and how the different disciplines are connected. The blue round boxes are connected to the logistic scheme, the red boxes are the flow of information, and the green circle is the design area of the scheme. It shows the route of the materials within a process from the deconstruction site, towards the depot, where it is stored. Next, the flow, if necessary, goes to the processing area, eventually returning back to the depot. When the design is created with the information of accessible materials at hand, it can be transported towards the new construction area (Franssen et al., 2018).

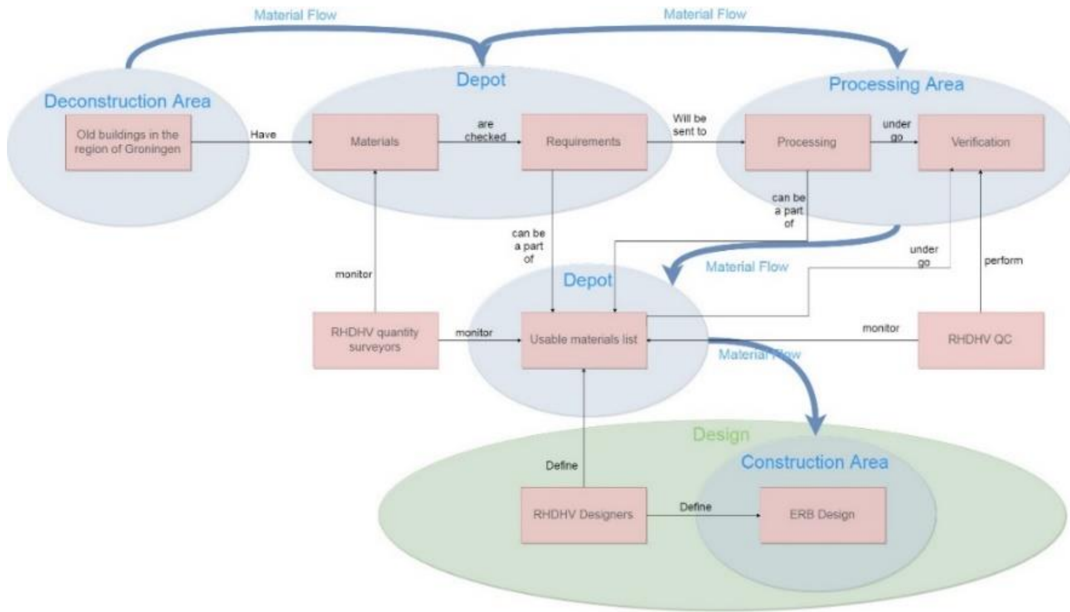


Figure 1.4 Material flow & Logistics flow (Franssen et al., 2018)

This project was initiated with the goal to provide a research problem to be solved within the graduation thesis. The case in Groningen showed the possibilities when a certain amount of information is available concerning building elements. The housing demand, on the other hand, is growing in the Netherlands and materials are needed to provide new dwellings. However, the gap between the information on housing demand and the availability of reusable building materials is too substantial. This gap is researched and discussed. These problems and related research goals are described in section 1.2.

1.1.4 ENERGY TRANSITION

Every new housing project that is initiated in the current time must keep the Paris Agreement in mind. It has been decided in 2015 that all the greenhouse gas emissions should be reduced to 80% in 2050, according to the low-carbon economy roadmap, through domestic reductions alone (EU, 2011). One of the overall goals is holding the increase in the global average temperature below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels (Fabius, 2015). The Dutch government established legal requirements among starting construction project for new dwellings, according to the climate agreement. The energy performance coefficient (EPC) of the dwellings should be equal or lower to 0,4 according to the government, which is an important step towards an (almost) complete stock of energy-neutral dwellings in 2020. This applies to the energy usage of the dwellings, which involves heating, ventilation, cooling, and lighting (Haytink & Valk, 2015). All the newly designed building, dwellings and utility construction, should meet the requirements for almost complete energy-neutral buildings (BENG), to get an environmental permit. These requirements will initiate on the first of July in 2020 (Rijksoverheid, n.d.-a).

This means many of the upcoming housing projects focus on an energy-efficient home design, designing multiple techniques to reduce as much of the emission as possible. Future dwellings will not be connected to gas in 2020, eventually with the goal to have all the dwellings cut off from gas by 2050 (Rijksoverheid, 2016b). An example that is developed, to react on the demands of the government, is to keep track of the energy usage with the Home Energy Score, developed by the U.S. Department of Energy (EnergySaver, n.d.), where each dwelling receives a score, based on its structure, heating, cooling, and hot water systems. The newly to build dwellings throughout an urban mining process should be designed of such quality that it complies with the regulations stated in the Paris Agreement. I directly combines the costs for a renovation, which would happen anyhow to answer to the new regulations. This creates possibilities to combine the use of leftover building materials with the demand for new dwellings, which could lead to a useful and achievable business case. It directly stimulates designers to innovate standardized dwellings, with the future perspective of the possibility to disassemble the buildings for future purposes. It could also provide subsidies or other financial investments from municipal organisations or the government, to support or fund a project that is in line with the Paris Agreement of 2015. These subjects are put at hand within the thesis' main research goal in chapter 1.2.3.

1.1.5 SUSTAINABLE DEVELOPMENT GOALS

In the same time period as the Paris Agreement, the United Nations set up the Sustainable Development Goals (SDG's) in 2018. These 17 SDG's are the blueprint to achieve a better and more sustainable future for all. Global challenges are all connected to the 17 goals and each of them are targeted to be achieved in 2030 (UN, 2018).

Figure 1.5 Sustainable Development Goals (UN, 2018)

The goals are connected to the main societal challenges to achieve a better future, including the building sector and the CE. Social enterprise Circle Economy, organized as a cooperative, described the connection to most of the SDG's to the CE. This has great potential to help meet global sustainability targets and the Paris Agreements goals (Thelen et al., 2018). The overview of the link between 8 of the 17 goals connected to the CE is described in Figure 1.6. The connection between these descriptions and the building sector shows a clear comparison. For example, SDG #3, good health and wellbeing, connects with the CE by avoiding and removing hazardous substances from material use cycles. Decreasing building waste in construction projects and reusing building materials in new projects is an example of how this goal could be achieved in a future CE. This could be an attempt to tackle one of the goals within the building sector. Another example is SDG #11, Sustainable cities and communities, where the CE focusses on repair and extending producer-consumer contracts. This design could be adapted in new building projects, instead of buying interior and movable products, change the system to leasing products for a certain period of time. The products will be retrieved by the owner after a certain contract, decided on the lease time. SDG #12 is also a perfect example of how the building sector and the SDG's meet. Responsible consumption and production focus on responsible care for products and that virgin materials are minimized, which is exactly the goal of this research.

The SDG's, which are set by over 190 countries, are meant to tackle climate change and should inspire businesses to act on the goals. However, the question arises how to get companies inspired to invest to join the fight against poverty, climate change and other targets (Hardcastle, 2015). It shows that only 16% of companies have explicitly assessed the implication of the SDG's on material issues (Davy & Guar, 2018). This is of course among all the companies, not only the building sector, but these companies and their effort which should be put in reaching the SDG's could be the missing link in the transition to a CE. Davy and Guar (2018) also mention 5 things that companies can do to realize the business opportunity from the SDG's:

- Assess the SDG's against company policies and practices.
- Use the SDG's to inform strategy development.
- Review the SDG's as part of target setting.
- Apply the SDG's to impact monitoring and measurement.
- Consider the SDG's as part of reporting, such as an SDG index.

The SDG's could be of stimulation for this thesis, to support certain choices made in relation to the transition towards a CE. During the answering of the main and sub-research questions, the SDG's are taken into account concerning closing the gap between the companies and the goals.

SDG		LINK TO THE CIRCULAR ECONOMY
3	Good health and wellbeing	The circular economy avoids and removes hazardous substances from material use cycles, decontaminating the economy and allowing recycling without risks to nature and human health (e.g. phasing out asbestos or the use of leaded paints).
6	Clean water and sanitation	Most of the circular economy principles on material reuse, recycling, resource efficiency and industrial symbiosis are equally applicable to water, thus increasing the quality and the accessibility of clean water.
7	Affordable and clean energy	Circular energy solutions result in reduced energy demand. Sharing energy, using geothermal energy, increasing buffering capacity and using of renewable energy sources changes the way we use energy and stimulates clean energy use.
8	Decent work and economic growth	New business models lead to new companies and job opportunities. Circular economy business models in which companies collect or take back, repair and refurbish products are usually more labor intensive than linear models and create additional job opportunities.[24,25] In many emerging economies, waste collection supports a vast informal economy that lacks safe working conditions and fair remuneration.
9	Industry, Innovation and Infrastructure	The circular economy requires large-scale innovations in the built environment. This relates not only to industrial or technical innovations but also to infrastructural innovations. Circular economy is part of the solution, making industry more sustainable and resilient at local and global scale.
11	Sustainable cities and communities	The circular economy, with its focus on local production, repair and leasing and extended producer-consumer contacts, requests a new, small-scale, spatial design to which cities should be adapted.
12	Responsible consumption and production	The circular economy requires that: responsible care for products extends to the use and the post-use phase; that use of virgin materials are minimized; and that programmed obsolescence is phased out.
13	Climate Action	The circular economy can contribute to GHG reduction in many ways. Using secondary materials instead of virgin materials often requires less energy when considering energy associated with extraction. For example, reusing steel instead of having to mine ore and process it into steel can dramatically reduce GHG emissions. In addition to this, circular energy production and water management are key in climate change mitigation and adaptation.

Figure 1.6 Link SDG's to Circular Economy (Thelen et al., 2018)

1.2 PROBLEM STATEMENT

In the current starting construction projects, most of the materials used for the dwellings are gathered from processing factories. The use of virgin materials is common among regular construction projects and has been used in most of the projects in the past. Considering the downgrade of the availability of some of the materials in the world other options should be researched (Kleinjan, 2017). Fossil materials are getting extinct, especially structural building elements (Rijksinstituut voor Volksgezondheid en Milieu, 2016). A new system of reusing different materials have to be considered to pursue environmental change. According to the possibilities of a CE, it should not be standard anymore to use virgin materials within such a big industry that produces one of the largest downgrades of valuable products and waste flows of leftover materials. The amount of waste in the construction sector will keep on increasing towards 2025 double to 2.2 billion tons (Slowey, 2018). Still the building sector is one of the bigger sectors that is lacking to innovate, compared to the other sectors (Agarwal, Chandrasekaran, & Sridhar, 2016). Still, multiple projects are over budget and over time, which shows the construction industry is ready for innovation in any way. Developing a system that connects information on the availability of building elements to the contractors would be an innovation to help improve the building sector. If there would be a so-called middle man who researches the number of materials available, it creates an interesting business case and could provide the connection which is missing, shown in Figure 1.7. In the current situation, multiple starting platforms are creating the role of the middle man adding value to the construction sector by connecting supply and demand. The platforms are relatively small market parties, testing their systems with a limited amount of stakeholders involved. There is much innovation possible in data management systems, but also a collaboration between stakeholders. Contractors and designers could pursue an environmental change in their company setup. Creating an overview and insight by investigating the feasibility would reduce the use of virgin materials, the amount of building waste and provides building projects from a circular point of view. Engineering and architectural companies would focus during their designs on the availability of existing materials and implement the technique into modern-day projects. This direct adaption of UM into the design process and the use of circular materials and processes could be a solution for future construction and design processes, considering the fact virgin building materials are less and less available in the future in the Netherlands (Kleinjan, 2017).

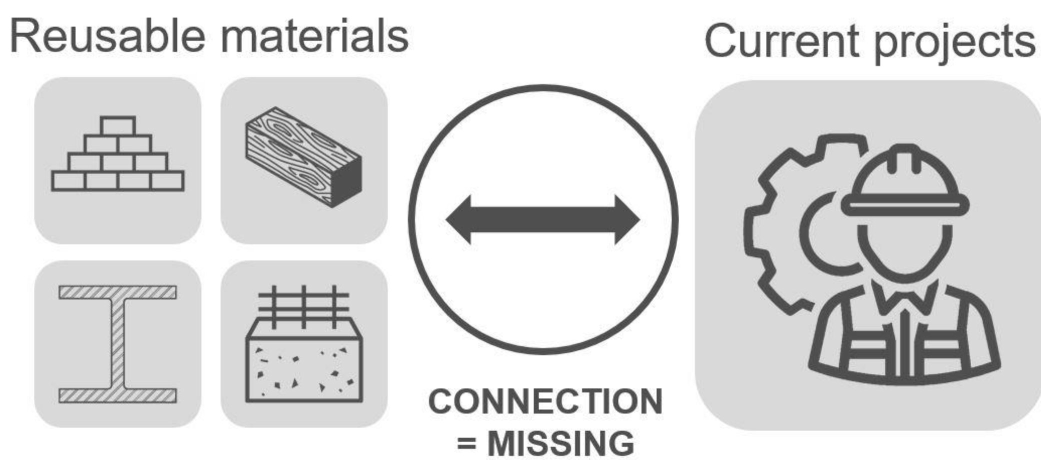


Figure 1.7 Problem Statement (own ill.)

This chapter focusses on the setup of the research question, based upon the problem statement that has been mentioned. The societal relevance and the scientific relevance of the research are elaborated in the first and the second section. The research question, together with the sub-questions are explained in the third section. Finally, the research goal, research deliverables and the setup of the research organisation are described.

1.2.1 SOCIETAL RELEVANCE

Multiple existing artefacts consist of usable building materials. However, not all of these artefacts are liveable, due to for example earthquake damage, which is the case in the Groningen example. The materials of these dwellings are of value for new building projects. Instead of demolishing the buildings, gathering the materials by using urban mining and using them for new projects could be a way to extend the lifespan of building elements. Reusing materials of buildings could have a positive effect on the emotional value for residents. The people of in this case Groningen could intend to move because of how they handle the experience of being struck by earthquakes (Jansen, Hoekstra, & Boumeester, 2017), but while reusing some of the materials of the old building for the new construction, certain memories and sensitive parts could be saved. It makes the process of the construction much more circular, by reusing the materials it generates a circular and sustainable design. The homeowners of Groningen experience a lot of burden because of the situation around the gas extraction and the multiple earthquakes (Wijnbergen, 2018). Creating a method for reusing the materials of dwellings in Groningen for new housing projects as circular and efficient as possible will probably gain support by the owners of the endangered buildings if the materials are being used in the right matter. Other (earthquake endangered) areas around the world with a lot of unused building materials could benefit from this methodology, keeping in mind that the context of every area is different. It depends per case what level of urban mining can be implemented and which stakeholders would take part in the organisational process. For the citizens of endangered areas, the societal relevance of these reconstruction projects is of a high level. For example, architectural firm MVDRV started a project in a village called Overschild, where Winy Maas and associates in collaboration with the residents of the village, developed a plan to strengthen the village that is damaged by gas extraction. What makes this project so unique, is that the residents of the village whose dwellings are not suitable for reconstruction are directly involved with a design of their new house in the same village, using elements of their former house within the new design (Maas, 2018).

The case of Groningen is just an example of how this system of construction can be of use in a certain regional area, where there is a lot of sensitivity and emotional value connected to certain buildings. In this case, reusing materials could solve construction problems without losing the emotional value of dwellings, which could be an argument of importance to pursue reuse of building materials for designers and/or contractors of new dwelling projects in Groningen. However, the reuse of building materials in other projects is of relevance as well, due to the transition to a CE and the in Paris set 17 SDG's (UN, 2018). SDG goal #9 and #12, 'Industry, Innovation and Infrastructure' and 'Responsible Production and Consumption' shows the need for large innovation in the building sector and the need for reducing the use of virgin materials to a minimum. Companies could use the SDG's as well to be funded by the government for projects that involve reusing building materials, because of the motivation of a company to join the road to achieve the SDG's.

1.2.2 SCIENTIFIC RELEVANCE

The knowledge on implementing used materials of existing dwellings into new building projects is not that far developed yet. In current projects, this method has not been used that much, or there is not that much information about it yet. The gap lies in the fact that this system could be improved. Whether or not this model could be financially an improvement to contractors is relevant. The possibilities of implementing these materials into the process and researching whether or not this could be a valid business case from the perspective of the middle man are also interesting and create possibilities for starting companies. The scientific factor lays within the operationalization of the system into new projects, researching the feasibility.

Another important factor that could be improved is the matter of sharing information on building materials. New projects could be started and mostly designed out of reusable materials, but if there is no information available or being shared by stakeholders that are in possession of this information, the stakeholders will not initiate using reusable materials as building materials and there will be no projects to start designing. Because of the confidentiality of the information, it is difficult to make the connection between the contractors and the designers. Multiple companies who are in the possession of information or datasets of different projects or material sets are in competition with similar companies. The demand for this material is getting bigger, which means it makes more sense for a company not to share the information about the available materials with other parties, without receiving compensation. However, the goal of a CE is to find a solution together to reduce waste and promote reusability of products. This is not possible if one of the most important stakeholders, meaning the companies that are in possession of the materials, keep the data to themselves, not participating in the circular mind. There should be searched some kind of solution, which makes government and private parties collaborate, without the fear of losing information and data systems to other clients or competition. This is where the gap lies within the structure of reusing materials on such a large scale and where further research could be conducted on how to solve this communicative problem.

1.2.3 RESEARCH QUESTION

As mentioned in the former chapters, there are a few challenges related to implementing the process of reusing building materials into traditional construction projects. This thesis researches the possibilities of increasing the circularity of these processes, to reduce the usage of virgin building materials in design and construction projects and help the construction industry with the transition towards a CE. The building materials that can be gathered by UM must be considered while initiating new projects and the overview of supply on existing building elements must be up to date. The feasibility of the process by adopting reusable materials into the design compared to virgin building elements is also of importance. The market has to be researched, whether or not there is a demand for this type of building materials or this type of system for contractors. It should be researched whether or not it is feasibly possible to adapt reusing materials to make it more cost-efficient, or more interesting according to the goals of the United Nations to receive funding. This is just a small list of the topics within this research, which in overall tries to clarify the challenges and research how the transition towards a CE could be stimulated in the building sector.

The problem statement combined with the societal and scientific relevance provides the following main research question:

How can an operational model link the supply of existing building materials with the demand for new construction projects in order to reduce the use of virgin materials and thereby improve circularity in the construction industry?

Figure 1.8 shows a conceptual model of the research at hand. The term UM is supported by the collection of the data. The data arises from the supply that consists of case studies coming from a project-, enterprise- or region-based level context. This supply provides neglected buildings that consists of building elements. These buildings elements are the reusable materials that trough UM will be used for new projects. A comparison of feasibility shows if the circularity of the building sector could be improved (Akadiri, Chinyio, & Olomolaiye, 2012). An extended explanation of the research model and how the research is interpreted in design and planning over time is elaborated on in section 3.1.

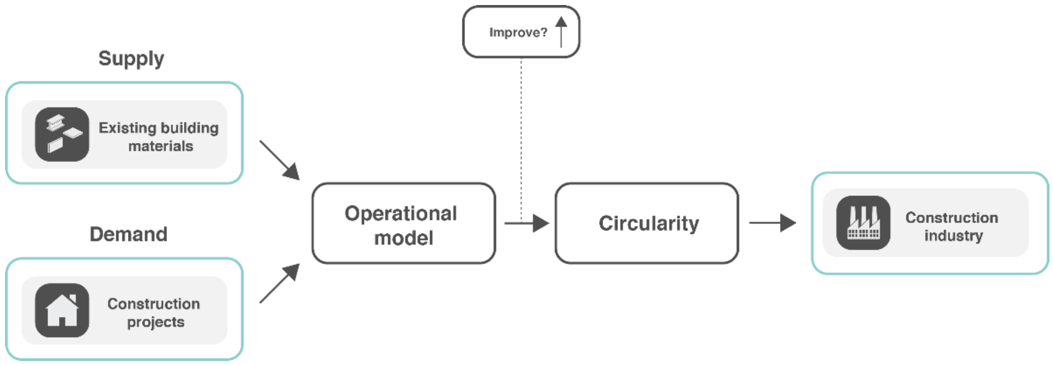


Figure 1.8 Conceptual model research question (own ill.)

In the following sections, the sub-questions based on the conceptual model are presented and briefly discussed.

1.2.3.1 SUB-QUESTION 1

What specifications are necessary for a case study to be implemented as input for the operational model?

The first sub-question focusses on the input for the model. The cases selected are divided into three levels of scale, which is analysed in section 2.3, before elaborating on the cases. The goal of the levels of scale is to provide results from diverse models at a various size and the possibility to analyse the models from a different perspective. The following deliverables of this sub-question are:

- An overview and analysis of all the available case studies.
- A clear demand on how the data required as input for the model should be organized.
- A substantiated choice on which case studies are and aren't used as input for the model.

1.2.3.2 SUB-QUESTION 2

What is the current demand in the construction industry for new housing projects?

The second sub-question focusses on the demand for new dwellings, based on the wishes from the housing market, but also on the possible innovations within the construction industry for new housing projects. This is elaborated in section 3.4. The following deliverables for this sub-question are:

- A literature review of the current status of the housing market.
- A clear overview of different prototype dwellings, with each prototype thoroughly substantiated.

- An overview of the materials of which the standardized dwellings consists of, showing the current potential and specifications of these materials.
- An overview of wishes from stakeholders for new dwelling projects.

1.2.3.3 SUB-QUESTION 3

How can a comparison between the overview of the cost of virgin and existing building elements for new dwellings provide a feasible business opportunity?

The third sub-question focusses on the development of the operational model. Especially the feasibility of the different assemblies of dwellings are compared. The comparison results in advice for a business case. This sub-question provides the following deliverables:

- A clear overview of construction costs for virgin building elements, based on sources.
- A clear overview of construction costs for results building elements, based on expert discussions and sources coming from practice.
- A comparison between the costs of reusable and virgin building elements.
- Substantiated overview of the determination of the costs.
- Clear explanation and guidelines on how to operate the tool and how to implement variables and constraints for the calculations.
- Setup of the interface for the tool for practice.

1.2.4 RESEARCH GOAL

The main research question of this graduation thesis is focussed on how the supply of existing building elements and demand for new construction projects can be linked in order to reduce the use of virgin materials and thereby improve circularity in the construction industry. Because of the mentioning of the word 'how' in the research question, it aims the research towards a solution space (Barendse et al., 2012). In this space, a solution for answering the research question is generated, based on the available factors that emerge during the graduation project. How the circularity exactly could be improved depends on the output of the different parts of the research design. The literature overview and the research on the demand side from stakeholders and consumers could provide an answer on a social level, while the operational model could provide a specific tool for improvement, which can be used in further projects such as Groningen and other area's within the Netherlands or the world, where housing associations or municipalities have the ambition to create housing projects related to the transition towards a CE. The objectives of this research consist of creating a realistic advisory tool, investigate enough collaborating stakeholders and discuss the possibilities of UM within dwelling projects. The goal of this research is to minimize the usage of virgin building materials in starting construction projects. How this goal can be achieved is elaborated and substantiated by literature research and experts discussion. The supply and demand of the research questions is connected to each other. Based on the input from real-life cases and suppliers, the model is substantiated. This creates a set of bottlenecks, such as gathering the correct datasets and figuring out the right numbers for feasibility, which have to be overcome. When the correct numbers can be found and a feasibility study is executed, determining whether or not reusable materials or virgin materials are less expensive, the research goal of reducing the use of virgin building materials could be achieved.

1.2.5 RESEARCH DELIVERABLES

The research goal, as mentioned in the former chapter, presents how this research is going to be of value within the transition towards a circular construction industry. It aims towards a reduction of the usage of virgin building materials. As mentioned in the problem statement, there is a connection between supply and demand missing in the construction industry. Because of the absence of this connection, stakeholders cannot engage in circular projects. This link, or at least a fraction of this link, should be fixed, which will lead to more collaboration between different entities, increasing the circularity of building materials, eventually leading to a CE.

The main deliverable of this research is to create a hypothetical advisory tool that gives an overview to the different companies on the connection between the supply of reusable building materials and demand of circularity in construction projects. This tool is developed with the help of operational research. The tool is tested on multiple scales, based on the level of scale, explained in section 2.3. The tool can be evaluated and tested, according to the following subjects:

- The tool is able to perform correct calculations and provide a realistic output.
- The tool is based on literature research and fills a missing gap in research.
- The input of the tool is determined by experts within the field of construction and building sciences.
- The tool can be tested by running calculations with hypothetical and realistic data.
- The tool is adaptable on case studies of different scale, size and context.
- The tool consists of multiple modules, focused on transportation, construction and material validation.
- The tool is able to be implemented into practice and used by companies as test cases.
- The tool has the potential to be further developed with multiple modules and real-life cases from practice.

1.2.6 RESEARCH ORGANISATION

This MSc thesis is related to the master track Management in the Built Environment, which is part of the Architecture, Urbanism and Building Sciences master of the Faculty of Architecture and the Built Environment of the Technical University of Delft. The research is carried out in one of the four domains of the master: Design & Construction Management. This is shown by the connection within the management of building sectors, designing a more circular process and improving the structure of current and traditional construction projects. The development of the decision-making model is related to the operations research methods course, which is also part of the master Management in the Built Environment.

The first mentor is Dr. Ir. L.H.M.J. (Louis) Lousberg from the Design & Construction Management department of the master Management in the Built Environment. His expertise is related to feasibility, planning and managing the design phase of construction projects. His goal is to integrate practice with education and research. Next to educating in project management and academic skills, he is also researching the design of project management.

The second mentor is Dr. Ir. A. (Alexander) Koutamanis from the Design & Construction Management department of the master Management in the Built Environment. His focus is on information management and computational design. Also, he is an expert on the topic of urban mining, publishing the paper 'Urban mining and buildings: A review of possibilities and limitations' in 2018.

The third mentor is Dr. Ir. R. (Ruud) Binnekamp from the Real Estate Management department of master Management in the Built Environment. He is an expert on designing operational models and helps to develop the decision-making model that is related to the operations research course that is one of the electives of the master Management in the Built Environment.

The research commenced at the company Royal HaskoningDHV, with the Joint Interdisciplinary Project (JIP). The mentor during this project was structural Engineer Koen van Viegen, which provided guidance during the setup of the research and was the mentor of the project team during the JIP.

The graduation company for the second part of the MSc thesis is Alba Concepts, a circular organisation focused on consultancy, management and project development, located at 's-Hertogenbosch. Alba Concepts provided information from cases that are used in the research and guidance throughout the graduation process. The main supervisor during the graduation internship was Jim Teunizen, assisted by Jip van Grinsven and several other colleagues from Alba Concepts.

1.3 CONCLUSION

The circular economy has the potential to become the standard in multiple sectors, but the construction industry still has a lot of improvements to make before it has the certificate of a circular industry. The problem statement and different research questions mentioned in the former chapter shows a framework within the construction industry which has the potential to become circular. The different topics mentioned which are of relevance for the problem statement are being researched in literature studies and practice, elaborated in chapter 2. Literature research is necessary to determine the context for the operational research, the setup of the input and the output for the model and the eventual framework in which the model will operate to deliver the overview of the possibilities among reusable building materials, in order to answer the research questions.

PART 2 LITERATURE STUDY

The following chapter introduces a literature study about the different topics which are relevant for the research. The different sections provide a combined view on the current situation of the construction sector and shows where there are still gaps within the literature, which are the basis of this research and why this research is scientific relevant. The goal of the research is to improve the construction sector and its transition towards a CE. The literature study explores the current status and the possible improvements to be developed. This overview and conclusion is used as a basis for the input of the decision-making model, which is elaborated in chapter 3. Each topic is analysed and visualized in the conclusion of every section.

2.1 URBAN MINING

As mentioned in the introduction of the research, construction projects are still very traditional. The industry has been criticized for its traditional approach, particularly the one-off approach to projects and the fragmented structure not being efficient (Vrijhoef & Koskela, 2005). There are not that many examples yet of projects that are completely designed with reusable materials, almost every project which is designed is being built with mostly virgin building materials. This is because the traditional building sector focusses the expenses of new projects on foundation costs, instead of the life cycle of the materials. They are not willing to invest in circular initiatives, because of other priorities or because it is often simply too expensive (Ten dam, 2018). This shows that the construction sector is set in his ways, very traditional and not yet adapting to the transition towards a CE that is about to come and happening in different sectors already. But if new projects should be integrated with materials that are not virgin, the materials should be gathered, coming from a specific place. They should be mined from somewhere.

2.1.1 DEFINITION

Gathering materials from existing buildings that could be reused for new housing projects is called urban mining (UM). This term is a relatively new concept in the construction industry. It has been mentioned as a fancier term to describe different types of material recycling from annually generated waste flows (Cossu, Salieri, & Bisinella, 2012). Products taken from buildings could contain different materials, such as steel, wood, bricks (Krook & Baas, 2013), but also, in the case of housing, complete parts that could directly be used instead of putting the materials to urban waste, which the construction industry and relating projects are largely responsible for in many parts of the society (Agamuthu, 2008; Li, 2015). These materials hidden in buildings are interesting alternatives for the raw materials that in general are used for construction projects (Koutamanis, van Reijn, & van Bueren, 2018). Any anthropogenic stock could be used as a source for UM, such as infrastructure, industries and out of use products and is an extension on landfill mining, which only focusses on the extracting and processing waste stored in deposits, such as municipal landfills (Cossu & Williams, 2015). So, implanting this term into constructing processes and reusing materials seems to be the next step, using it as a strategic component of sustainability and circularity to improving the processes (Arora, Paterok, Banerjee, & Saluja, 2017; Cheng, Hsu, Li, & Ma, 2018).

In the current construction projects, UM is already adapted, but in a basic manner. The gathering of old materials and using those materials in a new project is simply what we call recycling. As mentioned by Koutamanis et al. (2018), it is stated that the performance of UM in resource recovery is already as high as it can get. On this level, it is not possible to improve the impact of UM, but looking at the situation from a different perspective could help. Organizing UM in the background process of AECO projects (Architecture, engineering, construction and operation of buildings) (Fox, Leicht, & Messner, 2010) still has possibilities (Koutamanis et al., 2018). The connection between the different phases and how UM in one phase is interpreted in the other phase shows the lack of overlap between the different project phases. If UM is being implemented by actors in different project phases, but collaborate in the project, it could improve the integration of the process. This depends on the scale of operation, project-based, enterprise-based or region-based, the amount of stakeholders and how much material is available in a project (Koutamanis, 2018). In the Groningen case, where materials could be gathered all over the province and the municipality is the main client and stakeholder in this case, the UM would take place on a region-based level. In this case, the houses are vacant or are becoming vacant, which is a good example of refined natural recourses in the form of building components and materials. These empty buildings can be used as reserves for housing and repositories for UM or material extraction (Huuhka, 2016).

2.1.2 CHALLENGES

It is a challenge to determine whether or not UM is possible to implement in other levels of scale. The demand for more circular projects is of importance if on a smaller scale and direct adaption is asked for. The UM of materials could directly be used within new projects on the same location. The transportation factor is low because materials could be directly reused on the exact same location. If UM would take place at a region or enterprise-based level, the transportation of the materials is of larger influence, cost-wise and logistic wise. Even with these factors included, the comparison with virgin building materials should be made to have insight in whether or not it is a feasible business case to use existing building elements. There has to be thoroughly researched and documented what kind of materials are located at certain building sites and if they could be reused in new projects, making sure there are no mistakes made by suppliers and contractors about the information of certain building elements. This information should be up to date and shared among all stakeholders, to make UM a serious option within new construction projects. If the materials or the waste of former projects are not of the needed quality, there has to be taken care of on-site processing, which is generally difficult and expensive (Koutamanis et al., 2018; Ulubeyli, Kazaz, & Arslan, 2017).

2.1.3 CONCLUSION

The different literature on UM shows that the term is still in development and could be of use within the transition towards a CE, but there is still a lot of information and knowledge to be gathered to be sure of the added value of UM in the construction sector. Every case is of a different context, which makes it difficult to develop a certain tool on the concept of UM that could be used in every project. Also, because the term is interpreted differently by stakeholders, it is unclear whether or not the term is the right way to go when talking about reusing building materials. A clear definition of the concept is necessary to have it being used on a large scale in projects. Also, the challenges mentioned in the former section concerning information about building materials and especially the transparency on data is a problem that is yet to be solved within the near future, to make UM a realistic way of future construction projects.

2.2 MATERIAL FLOWS IN THE CE

When the construction industry mentions the transition towards a CE, the suggestion is made that most of the materials within the building sector have a linear lifespan and are not being used circular yet. The material flows mostly are being used for a single purpose, before they are being demolished or disintegrated to landfill, turning into waste that cannot be reused anymore and eventually being transformed to energy or even being burned or deposited, which are the lowest classification on the Ladder van Lansink (Lansink, 1979), which is used in the European Waste Framework Directive since 2008 as general guideline for the classification of waste flows. The European Union has mentioned making it its mission to face the challenges relating resource scarcity and shift from a linear to circular systems, whilst regarding waste as a recourse (R. J. Geldermans, 2016). So the waste of materials flows and flows itself should be reinvestigated and researched, to make sure only the highest classifications of the Ladder of Lansink are at stake for these materials (Figure 2.1).

Figure 2.1 Ladder van Lansink (Lansink, 1979)

So what schematic flows on the transition to the circular use of materials are already existing? An example is powered by Cradle to Cradle®. Figure 2.2 shows how the material flow of techno sphere and biosphere materials would work in a CE. In this system, no waste is being produced and the materials are either being used as renewable energy or as know-how, the feedback loop to redesign & prototype the product, after collecting it when a certain material fulfilled its lifespan (Brey &

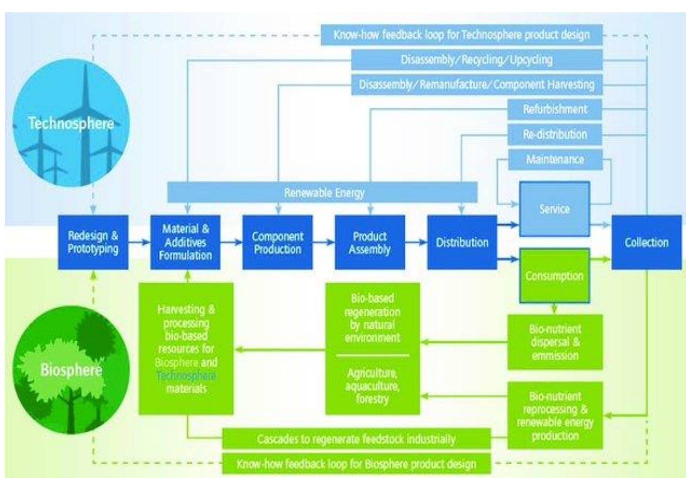


Figure 2.2 Material flows in a circular economy [Source: EPEA & Returnity Partners] (R. J. Geldermans, 2016)

Hansen, n.d.). It shows an excellent example of the different paths materials take to recreate value within their lifespan and that material, from a biological or a technical nutrient, can still be of value even if it the material is not being used in its primary function.

Figure 2.3 shows a similar scheme, where especially the minimization of the landfill is being highlighted (EMF, 2013). The arrows on the right illustrate the circulation of materials in technical cycles. These range from maintenance of existing products, to refurbishment and lastly recycling. The longer an arrow the less sustainable the option presented (Isaac, 2018).

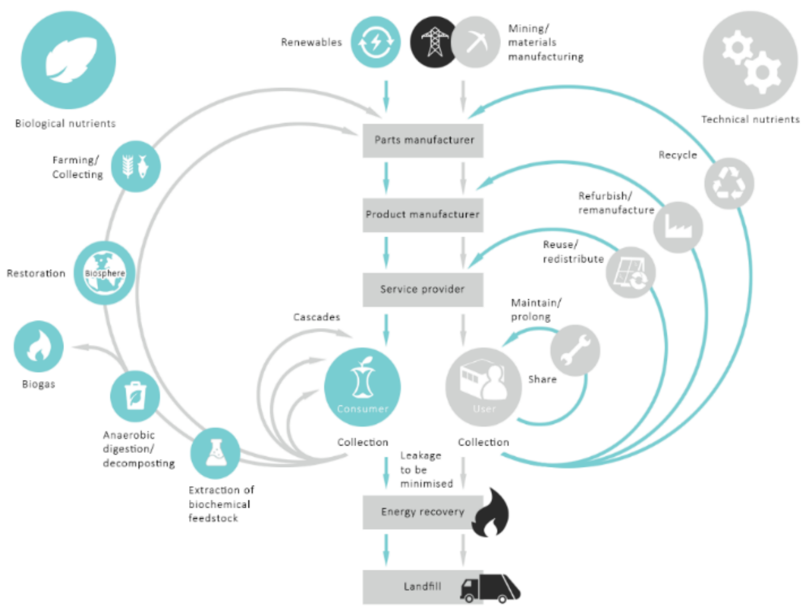


Figure 2.3 The circular economy—an industrial system that is restorative by design (EMF, 2013)

Cheshire (2016) proposes a gradation of the steps of what is possible with materials when their life cycle is completed. The gradation consists of six levels of material utilization, visible in Figure 2.3, which are CE principles applied to the built environment. This concept of gradation of the action to be taken for materials could be implemented into the construction industry, as Cheshire (2016) proposes. The concentric circles represent the technical and biological loop (van Vliet, 2018). The 6 steps of material utilization are:

- Retain
- Refit
- Refurbish
- Reclaim/reuse
- Remanufacture
- Recycle/compost

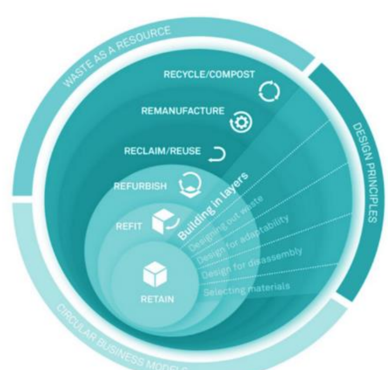


Figure 2.4 Applying Circular Economy principles to the Built Environment (Cheshire, 2016)

2.3 LEVEL OF SCALE

Reorganizing the construction industry is considered to be a long-term objective for a country, regarding the transition to a CE and the many different processes that are integrated within this sector. To create a system to support the entire building sector, it is important to realize not all the different aspects can be handled at once. It takes time and multiple steps to transform a traditional, linear industry into a circular industry. This is also relevant for the scale of the project, on which level of scale a certain revision of a system would be implemented. The level of scale depends on what type of case studies could be used for the testing and development of new construction industry techniques, giving insight how much of the processes could be improved, in line with the transition to a CE. This could, in small steps, trigger the construction industry to innovate and follow another sector such as finance, transportation or healthcare, that are actually seeing the potential in technology and grasp opportunities to boost productivity and commercial gain (Robinson, 2018). In the next sections, three levels of scale are elaborated: The project-based level, region-based level and the enterprise-based level (Koutamanis, 2018), illustrated in Figure 2.5. For every level of scale, a short elaboration and an example project are illustrated.

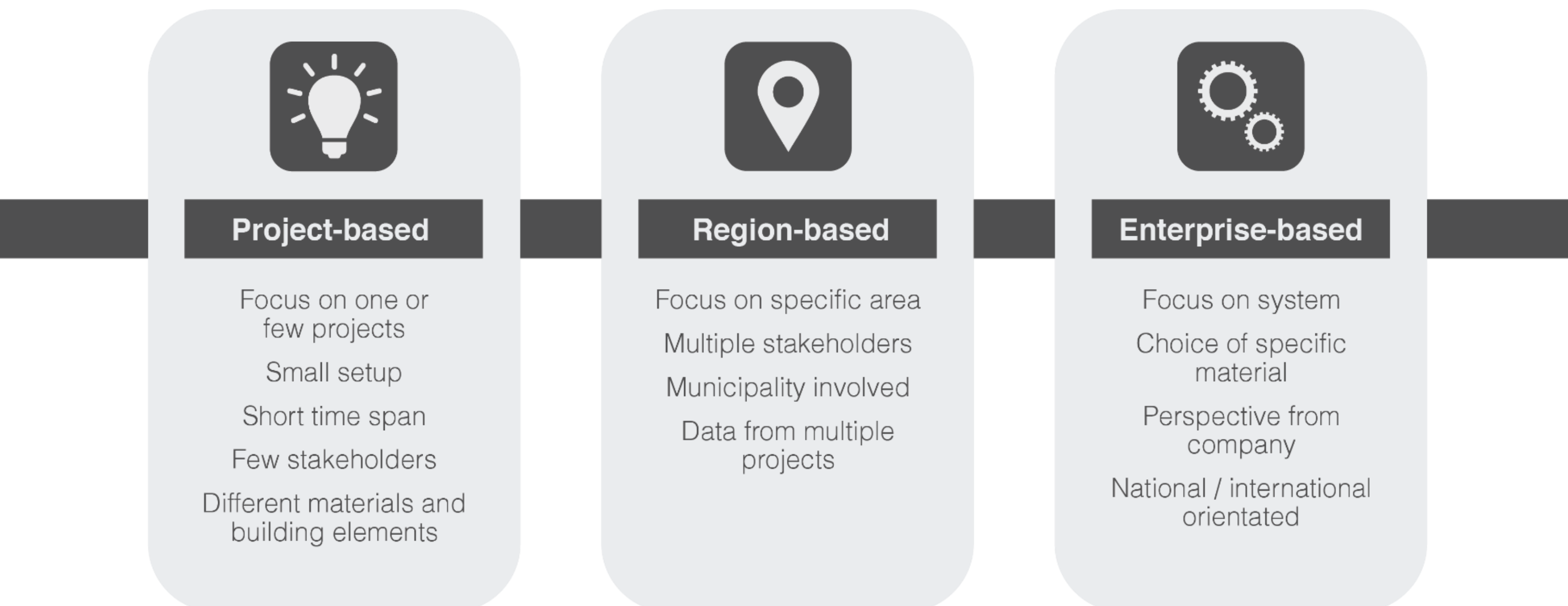


Figure 2.5 Levels of Scale (own ill.)

2.3.1 PROJECT-BASED LEVEL

The first level of scale is the project-based level. In this level, the context is based on one or just a few projects, to deliver input of data for a particular model. This model could deliver a solution for a small setup of a project, which could find the solution within a short time span. The area that would be focused on in project-based levels is relatively small, so subjects as transportation of materials are of a smaller factor. The materials from certain cases could directly be used for a new project, which could be at the same or a close location and it of the same size or scale, compared to the existing projects, which is being used as a case study. In this case, not that many stakeholders have to be involved within the collaboration, making the transition of the materials efficient, reducing the number of intermediary's. The number of different materials and building elements can be of a wide range, aiming to reuse as much as possible within the new projects. An important innovative design decision that should be made on this scale of projects is to implement the possibilities of materials available to reuse within the design phase of the new projects. In this case, there would already be a new destination for most of the parts of building elements, which are still located within the current buildings.

An example of a project that is designed and build conforming the circularity standards of the current age is the Green House in the station area of Utrecht. A collaboration between Albron, Strukton and Ballast Nedam, following the design of architectural firm Cepezed, created the completely circular and extremely sustainable pavilion with hospitality and meeting functions (van der Voort, n.d.). The pavilion has a lifespan of 15 years, at the end of this time period the complete building should be exploited and because of its focus on circularity, the design of the Green House is completely detachable. This makes it possible to deconstruct the pavilion and rebuild it, in a different or the same shape on a different location. The materials that are used to construct the building are reused as much as possible. The rest of the elements are acquired by lease, still in possession of the supplier, creating a complete circular business model (van der Voort, n.d.). This project is an example of a project-based scope, collaborating with the designing firm about the qualities of the future building. The parties decided on a circular building, looking for materials that could be used and adapt the available materials into the design decision. For example, the curtain wall used for the Green House is retrieved from the former Knoopkazerne, which was just next door (Duurzaam Gebouwd, 2018). A combination of the reuse in projects that are close by is an effective solution for project-based level cases.

Figure 2.6 The Green House (Duurzaam Gebouwd, 2018)

2.3.2 REGION-BASED LEVEL

The second level of scale is focused on a region. A specific area within a province or a country is the basis for the data input and the data will be of a larger proportion compared to the project-based levels. Multiple stakeholders have to be involved, because of the larger size of the projects and the multiple information points that is part of the research. A municipality or larger housing corporation should be involved to carry out a project on a regional level. The collaboration between the multiple stakeholders is of great importance. The datasets should be shared and the demands for new projects should be aligned. If so, the information coming from different existing projects could be assembled and exploited in the best division of projects.

The case of Groningen explained in chapter 1.1.3 is an example of a region-based project. In this case, the information on the materials has been gathered by a certain stakeholder and the demand for new buildings is coming from the municipality. A sufficient amount of buildings was (partly) demolished by the earthquakes. These shocks by gas extraction are still going on, disrupting houses and creating an insecure living situation for the residents of Groningen (Nu.nl, 2019). Even though the buildings are damaged, most of the building materials are still intact and ready to be reused. A collaboration between multiple stakeholders could be the solution to the problems of such an area. You would need a stakeholder that could analyse the buildings which are (partly) destroyed and that could make an inventory of the usable building elements. The municipality should be responsible for the demand and financial structure for new dwellings for the residents within the area. A structural engineering firm or an architectural firm should be in charge of designing earthquake resisting dwellings, which could be circular designed by using the inventory of the existing building elements. This would create a circular business model, benefitting on fewer transportation costs, less processing costs and less use of virgin building materials, instead of reinforcing dwellings with wooden beams, which is not a circular and effective solution (Figure 2.7).

Figure 2.7 Earthquake damaged dwelling at Groningen (KNAG, 2016)

2.3.3 ENTERPRISE-BASED LEVEL

The third scope level is based on the concept of an enterprise. An 'enterprise' means a unit or business organisation or activity, especially a business organisation (Enterprise, 2003). In this case, the enterprise scope would focus on a system of a certain material or multiple materials, which could be used for different projects over a considerably large area. The business case is the implementation of the waste of a specific product, which could be of value for other sectors, the material being used in a different function. From the perspective of the company, materials could have value, while for different stakeholders the same materials belong to their local waste streams. This creates a more circular flow of materials. A similar concept is possible within other sectors as well, such as the construction sector. A company or enterprise could be leading on the availability of reusable elements from a certain material, being used for a specific part of new buildings.

An example of a company who was looking for a specific type of waste that could achieve much more than landfill is the company bio-bean. Instead of in the construction sector, bio-bean sees opportunities in the waste of coffee beans and turns this waste into value, advanced biofuels and biochemicals. The company, based within the United Kingdom, has found the link between different sectors and turns the landfill of the first sector into value for certain other sectors, by creating products from as much waste flows of coffee beans that could be achieved before putting it to landfill. Examples of products created out of coffee waste are the high-performance, sustainable heating briquettes Coffee Logs^{tm} (Figure 2.8), biomass pellets that are carbon neutral and used for industrial-scale heating, and biochemicals for a range of commercial purposes (Harrison et al., 2016). The entire country could perform as a case for the employees of bio-bean because coffee waste can be found everywhere and nobody is using it as a resource for products.

Figure 2.8 Coffee Logstm, product by bio-bean (Harrison et al., 2016)

2.4 MATERIAL MANAGEMENT SYSTEMS

The concept of having one department within a company responsible for the flow of materials, from supplier through production to consumer, is relatively new. Although many companies have adopted this type of organisation, there is still a number that has not (Arnold, Chapman, & Clive, 2008). This function within a company is called material management and provides possibilities for a company to improve the profit and the reusability of materials. In the transition to a circular construction industry, information about the building materials that are present and the management of the in- and outgoing materials within a company's structure are of great importance to reach a fully circular system. These materials passports are important for clear communication and collaboration between for example contractors and design firms. The difficulty within this information is the competition that consists between the different parties. There are multiple systems currently being developed, creating the problem of a non-fully integrated market in material passports. The developers of the material management systems are seeking to invent the most optimal system or platform, which could have an entire country or even bigger integrated. The consequence of this market is a decrease in interaction and collaboration between different sectors and stakeholders.

The call for a CE and innovation in the construction industry should encourage the competing stakeholders to collaborate and share the information, generating an integrated flow of material information. To classify information on building materials would become unnecessary and every interested stakeholder could browse between all the different available materials. Unfortunately, this would imply that an entire structure of the financial market and competition that drives these markets and innovation would be obliterated. The factors that stimulate private companies to develop systems and thrive for innovation in the building sector would not remain to exist.

2.4.1 MISSING OF THE 'MAN IN THE MIDDLE'

As mentioned within the problem statement of this research, there is a missing connection between the demand for new projects and the information on materials that are available to be reused. In the current economy, the platforms that are being developed focus only on the companies which are eager to join the organisation, while the construction companies, such as contractors or developers are only interested in discovering the most profitable price for materials. The responsibility of creating the link between both sides is not assigned to anyone. This missing of the 'man in the middle' concept creates an interesting business case. A third party could provide a link between the different parties. This stakeholder could be commissioned by the collaboration to research the link between supply and demand on building materials. First, there should be transparent information coming from the owners of materials available for reuse and on the other hand, there should be a clear demand for building materials for new projects. The business case focusses on the efficiency of the process, which could be improved, saving time and costs within production and processing, even transportation. The middle man could design an advisory tool that could modulate the reuse of the materials from a specific stock promoting the efficiency and advantages of reusing materials. The strength of this concept lies within the fact that it creates a service that is not yet existing. It combines the demand within different aspects of the construction industry, connecting parties that normally do not collaborate. Multiple existing companies have experienced successes and development from an idea to create a service for a not yet existing solution to the demand. For example Airbnb, an online marketplace that creates a connection between the demand for holiday apartments and the supply on private dwellings, offered by the owners. Also Uber, a company which offers services such as peer-to-peer ridesharing, but also ride service hailing, food delivery and a bicycle-sharing system (Uber, n.d.), reacted on the demand of visitors in cities and created the connection with providers. A Dutch example is 'Marktplaats', which gives people the possibility to buy and sell second-hand products. Every transaction is between customers, so the only responsibility of Marktplaats is providing a safe and transparent negotiation environment, creating a connection between supply and demand.

Figure 2.9 Airbnb / Uber / Marktplaats

So these are examples on different sectors, but there are also already many different systems and platforms available on building materials, which are partly up and running, but also some of the systems are still yet to be developed. The following sections provide an overview of the different systems and platforms, related to the construction industry.

2.4.2 MADASTER

'Waste is material without identity', quoted by Thomas M. Rau, one of the authors of the book 'Material matters; Het alternatief voor onze roofbouwmaatschappij' (Rau & Overhuber, 2016). The book describes the transition to a new economic system where consumers are no longer owner, but a temporary user of products and materials. Madaster was based on the concepts and insights described in the book (Madaster, 2019).

Figure 2.10 Madaster logo (Madaster, 2019)

Madaster is the cadaster for materials, making sure raw materials are being documented so that they can remain unlimited. A material passport for all the materials within certain buildings is created so that every material gets an identity and could never disappear into waste. The platform Madaster acts as a library where all the passports are stored and generated. The platform is independent and being developed under the supervision of the Madaster Foundation (Madaster, 2019).

To make use of the Madaster platform as a company, a subscription gives access the construction data online. A certain price related to the number of users and the total gross square meter of a specific part of real estate are generated and the minimal subscription of the platform has a minimum duration of a year. The platform is also available for private individuals, which enables you to make a dossier for your own home (Madaster, 2019).

The Madaster project is a Dutch non-profit foundation with an aim to eliminate waste. The project has received funding from the European Union's Horizon 2020 research and innovation program (Madaster, 2019).

2.4.3 CIRDAX – RE-USE MATERIALS

The second tool is designed by the company Re Use Materials, located in Heerlen in the most southern province of the Nederlands. The 'Cirdax' tool is a material management software, aspiring to be the first national system that makes it possible to manage materials during every step of the way in a real estate process. The focus within the tool is efficiency and efficient use of raw materials within demolition, construction and maintenance processes. The software of the tool includes multiple tools and methods to create insight within the materials (Re Use Materials, 2019). A difference between Cirdax and Madaster is the fact that Cirdax also provides assistance with clients in the follow up of the reuse of the building materials, by offering a (BIM) design tool and a social return tool. Madaster works as a market place for materials, but Cirdax gives insight in design possibilities, but also measurement on circularity within the realization of the new buildings.

The tools that Cirdax uses are described and visualized in Figure 2.11. The first three tools are up and running, the other tools are still in development by Re Use Materials, but still give an idea of what skills the tool will possess in the near future.

- **Assessment app:** Assessment of the materials, which are being added into the system. The app (iOS) makes it possible to identify the materials at hand.
- **Material passport:** Gives identity to the materials. This identity is determined by specifications such as quality, quantity, dimensions, color recyclability and detachability of the material. All of these passports are stored in Cirdax, which grants accessibility at any time.
- **Performance dashboard:** Visual representation of the performance of the tool, based on circularity, finance, carbon dioxide emissions and social return.

Figure 2.11 Overview Cirdax tools (Re Use Materials, 2019)

The tool is yet to be developed even further and is only accessible for clients who are in collaboration with Re Use Materials. It is not possible to log in or review the system of Cirdax when you are not involved directly with the company, so, unfortunately, it is not possible to review the actually developed software of the tool, because of its restrictions. It creates a perfect example of the current status of the CE in the construction industry. The lack of accessibility and transparency about building information or material management tools is still a difficult border to pass.

2.4.4 EXCESS MATERIAL EXCHANGE (EME)

The third example is the Excess Materials Exchange (EME) platform, which is a digital facilitated marketplace where companies should be able to exchange excess materials and products. EME tries to solve the problems mentioned of lack of transparency, lack of reliability and a lack of connection by developing the following products: a material passport for all the recourses, tracking and tracing of materials, a valuation module and al assisted matchmaking. By giving materials identity and providing a location where data of a product can be collected through every step of its lifecycle, there is actual information about the possibilities of each material and its location throughout value chains. The blockchain technology, which can be illustrated as a distributed database of records or shared public/private ledgers of all digital events that have been executed and shared among participating stakeholders (Crosby, Nachiappan, Pattanayak, Verma, & Kalyanaraman, 2016; Saberi, Kouhizadeh, Sarkis, & Shen, 2019), stores and secures the data, while the al assisted matchmaking will try to connect within different sectors. Waste in one sector could be of high value for other sectors. The matchmaking process looks for the most optimal reuse opportunities for any type of material (Damen

& van Maaren, 2018). The EME focusses on the area of the Amsterdam Metropolitan Area (AMA). Within this region, six priority types of materials are taken into the transition to a CE, which are: Textile, biomass, construction/demolition, E-Waste, plastic and diapers. These six flows of materials are being observed in the following six sectors: Services, tourism, industry, consumer goods, building and biomass (RoyalHaskoningDHV, 2018). But next to the waste flows, EME focusses on any possible reuse of material types and already pursued a lot of pilots to review the possibilities. For example, neglected carpet pieces or peels of oranges. Multiple companies have been involved within the testing and developing of the platform, such as Heembouw, Schiphol, ProRail, DSM and Rijkswaterstaat (van Doorn, 2018). Such as Cirdax, EME is still developing and hasn't optimized all the factors of the platform yet.

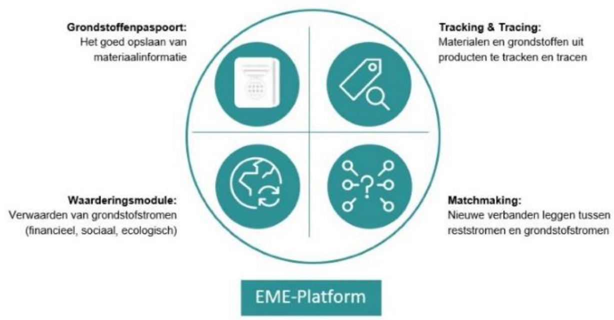


Figure 2.12 Excess Materials Exchange logo and modules (Damen & van Maaren, 2018)

The EME-platform provides four modules, visible in Figure 2.12, which are crucial for lifting the barriers between companies and providing them a chance to join the transition towards the CE. The first module is the material passport, which identifies materials and records the relevant specifications of the materials into a database. Next, the tracking and tracing system makes sure the information on when and where materials are being released is up to date, providing the most optimal transportation routes and up to date knowledge for possible distributors for the materials. The valuation module gives an insight into the financial, social and ecological value of the materials. Based on this information, information coming from the residual flows could be adapted into the design process, which is called reverse engineering. This will directly increase the value of the residual flows. The fourth model provides the matchmaking between supply and demand, creating a marketplace for secondary materials and providing information on whether or not the residual flow of materials could be reused. Stakeholders could place an ad requesting materials, but also offer their materials to other interested stakeholders, which are connected to the platform.

2.4.5 CONCLUSION

The former mentioned platforms or modules are just a small grasp out of the many different systems that are being developed throughout the world. It shows the demand for a CE and the motivation for multiple start-ups and companies to be the leading expert in reusing material systems. This provides an interesting market with competing companies, trying to win over clients to join their own developed system. However, as mentioned within the introduction of this chapter, competition should be exchanged for transparency and collaboration, to achieve a complete circular industry on building materials. The problem is the commercial interests for the typical marketplaces. This provides a business model that stimulates the companies to keep on developing these platforms.

When all the residual waste flows and information sets on available building materials are being made transparent, there should be a different business model for the companies to keep the innovation flow going. This is a challenge that is still yet to be solved.

2.5 DEFINITION OF BUILDING ELEMENTS

The internship company Alba Concepts provided insight in the 'Building Circularity Indicator' (BCI). The BCI is an assessment model that aims to provide guidance during the decision-making process to concretize the circular ambition of different stakeholders (Verberne, 2016). The structure of the model is developed by adopting the basis of the material circularity indicator (MCI), by the Ellen Macarthur Foundation & Granta Design (2015). The model provides the next step towards measuring how well the principles of the CE are implemented in a building project (van Vliet, 2018).

For this research, the practical version of the academic model, developed by Verberne (2016) and van Vliet (2018), is currently being used by Alba Concepts in practice. This model is elaborated, analysed and connected to this research in the following sections. During the development of the assessment model, it was of importance to discuss in different level of details with stakeholders on the subject. This ensured a set of definitions used for the different parts of the building, which are defined based on models from literature. These definitions of the building elements are elaborated and implemented in further development of this research.

2.5.1 BUILDING LEVELS

There are multiple definitions of the structure of the building levels and mentioning of different components. This creates a lot of haziness between stakeholders, discussing data in the construction industry. The research of van Vliet (2018) aims to use classification for building materials to differentiate between detail levels in an objective matter. This classification consists of multiple different from literature adopted overviews, eventually being used in the BCI in practice. The

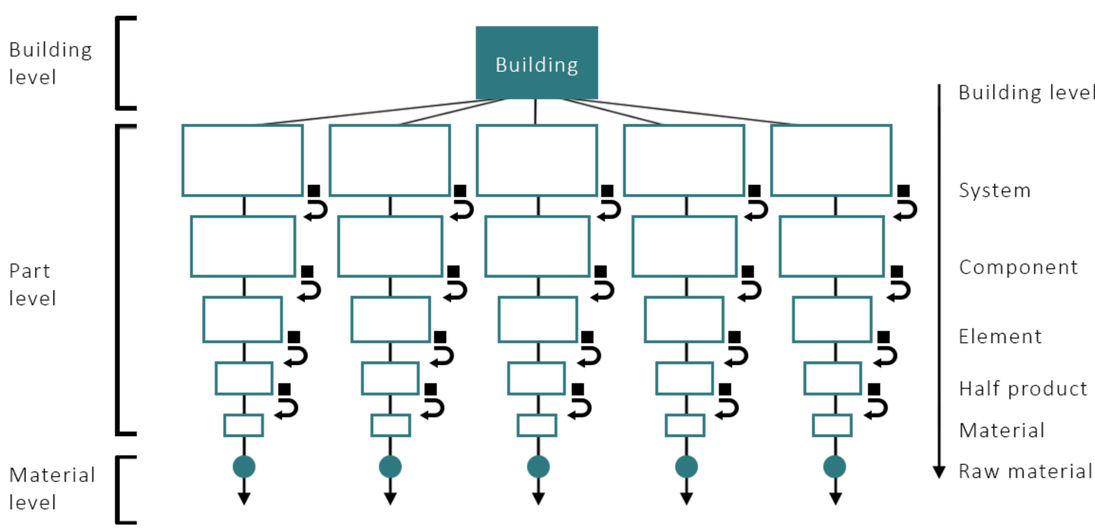


Figure 2.13 Theory of material levels (Durmisevic, 2006)

Shearing Layers of change (Brand, 1994)

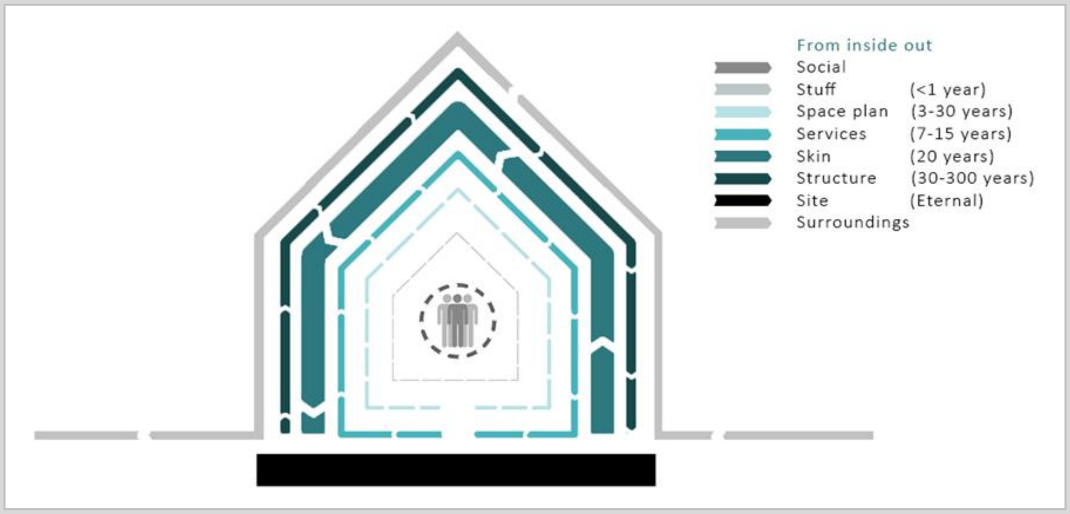


Image source: Alba Concepts (2018)

Site: This is the geographical setting, the urban location, and the legally defined lot, whose boundaries and context outlast generations of ephemeral buildings. “Site is eternal”

Structure: The foundation and load-bearing elements are perilous and expensive to change, so people do not. These are the building. Structural life ranges from 30 to 300 years (but few buildings make it past 60, for other reasons).

Skin: Exterior surface now change every 20 years or so, to keep up with fashion or technology, or for wholesale repair. Recent focus on energy costs has led to re-engineered skins that are air-tight and better-insulated.

Services: These are the working guts of a building: Communications wiring, electrical wiring, plumbing, sprinkler system, HVAC (heating, ventilating, and air conditioning, and moving parts like elevators and escalators. They wear out or obsolesce every 7 to 15 years. Many buildings are demolished early if their outdated systems are too deeply embedded to replace easily.

Space Plan: The interior lay-out – where walls, ceilings, floors and doors go. Turbulent commercial space can change every 3 years or so; exceptionally quiet homes might wait 30 years.

Figure 2.14 Shearing Layers (Brand, 1994) level to building level, which is also complementary to the NEN 2660:1996 top-down and bottom-up overview (NEN, 1996).

The shearing layers overview by Brand (1994) is a well-known method for describing the different building layers from inside out, combined with the expected lifespan of each layer. A brief elaboration of each layer is described by Brand (1994) in Figure 2.14. The overview is very generic and it does not require specific definitions for everybody to classify a building material (van Vliet, 2018), which makes it an applicable overview for defining materials to layers. Based on the assumption that these layers have different life cycles, design decisions can be made regarding their end of life scenarios (van Vliet, 2018). The different lifetimes result in multiple moments during the lifespan of a building when different components have to be replaced, some components more frequently than others (Brand, 1994). This creates the opportunity to look at the building in a more circular matter and see what the possibilities are concerning the circular ambition of buildings.

Where (Brand, 1994) proposes an assembly or disassembly, which is necessary within the process of calculating the BCI, on functional decomposition, Durmisevic (2006) proposes a physical decomposition. Figure 2.15 shows an overview, where the levels of a building are ordered hierarchical. In these three pyramids, a visualization is presented of three different divisions of building the structure. The first shows that the structure of materials is fixed, the second partially fixed and in the third pyramid, the structure of materials is completely open to disassemble individually (Durmisevic, 2006). These multiple building levels from literature, which are part of the development of the BCI is taken into account further within this research, in determining which materials to use.

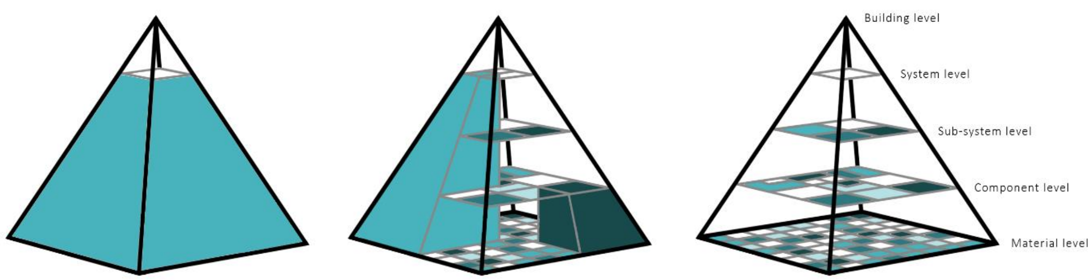


Figure 2.15 Fixed, partially fixed and open structure on different building levels (Durmisevic, 2006)

2.5.2 BUILDING CIRCULARITY INDEX – PRACTICE MODEL

The BCI as used by Alba Concepts in practice to provide guidance during the decision-making process to concretize the circular ambition of different stakeholders is designed by Verberne (2016). This section shows the theoretical and conceptual model of the tool. The BCI as mentioned is a theoretical model developed to create a simple measure of achievement to enable the transition to a CE (Verberne, 2016). The BCI focusses on the technical cycle in the CE model and defines a sum of key performance indicators that are included in the calculation model, displayed in Figure 2.16. This model presents the theoretical requirements of the BCI, essentially broken down into four steps (Verberne, 2016);

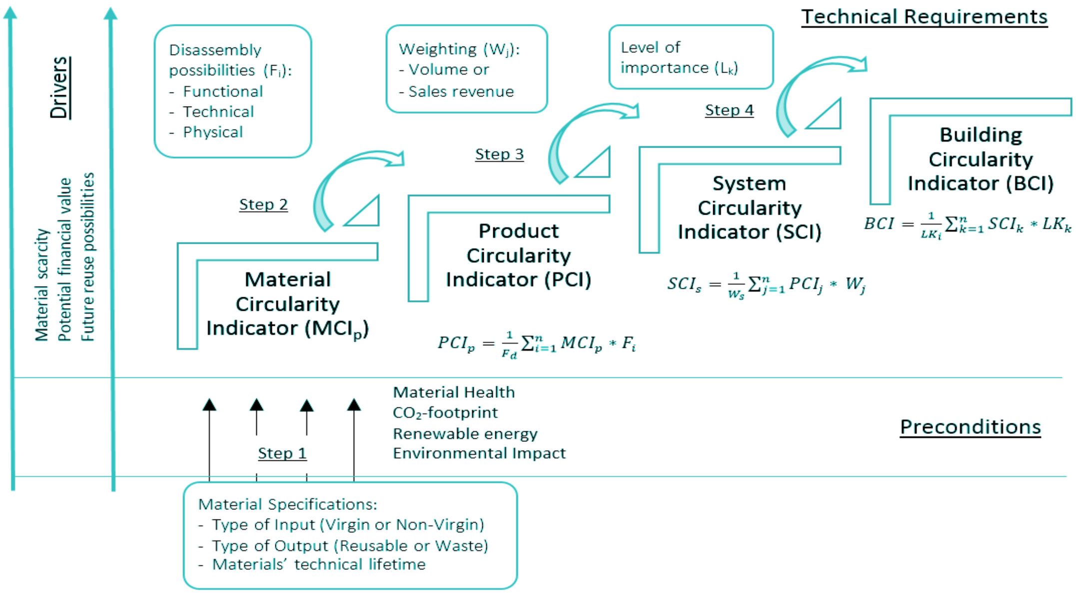


Figure 2.16 Conceptual model of the Building Circularity Indicator assessment model (Verberne, 2016)

- Calculate the Material Circularity Indicator (MCI) with the material input, output and lifecycles of products.
- Calculate the Product Circularity Indicator (PCI) by determining the disassembly possibilities of products and multiplying this with the MCI of the products.
- Calculate the System Circularity Indicator (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.

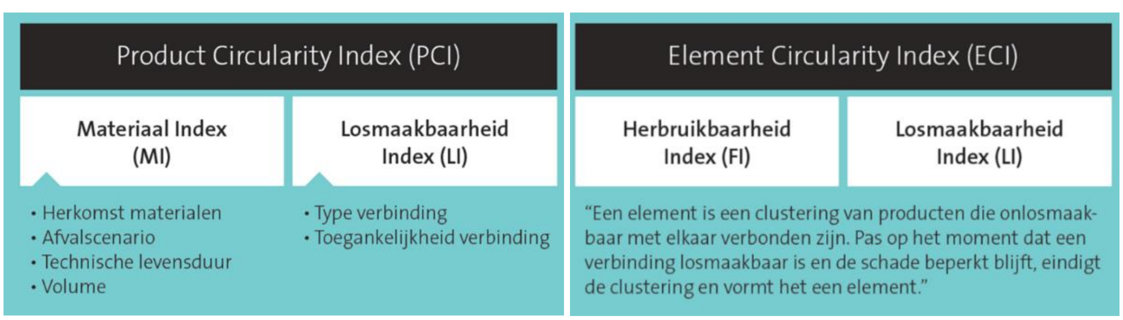


Figure 2.17 Product Circularity Index & Element Circularity Index (Alba Concepts, 2018)

The theoretical model of the BCI assessment model is adapted and transformed by Alba Concepts (2018) into an understandable model for practice. This model assesses the circularity ambitions of clients in a couple of steps. First, a list of key performance indicators, in Figure 2.19 described as drivers and preconditions, are presented. To eventually calculate the BCI, the PCI and ECI have to be determined. The PCI (Product Circularity Index) is determined by the Material Index (MI) and the disassembly potential. The MI describes the origin of the material, whether the materials are virgin or non-virgin, it describes the future waste scenario (landfill/incineration/recycling/reuse), the technical life span and the functional life span. The disassembly factor describes the type of connection between materials combined with the reachability of these connections within the product. Appendix 11.8 shows an overview of each type of connection with a different factor to be calculated with, based on the disassembly list of connections (Durmisevic, 2006; van Vliet, 2018; Verberne, 2016). The ECI (Element Circularity Index) describes elements as clusters of products, which are inseparably connected to each other. Once the elements are able to disconnect from each other without damaging (to a certain level) the products, the cluster ends and creates a new element. The amount of reusability combined with the disassembly potential defines the ECI.

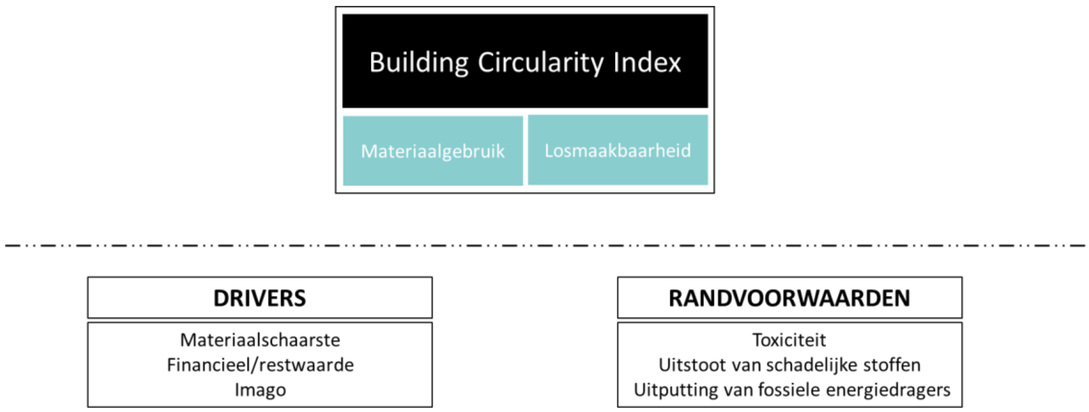


Figure 2.19 Building Circularity Index Drivers & Conditions (Alba Concepts, 2018)

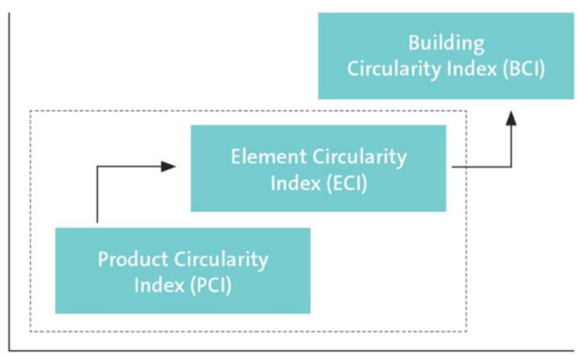


Figure 2.18 Building Circularity Index Calculation steps (Alba Concepts, 2018)

2.5.3 CONCLUSION

The different factors described within the theoretical and conceptual model of the BCI are based on literature and attempts to create a general overview of definitions for different components of the construction industry. This substantiated universal language of construction terms is something that has the potential to be infiltrated within multiple companies who tackle the same issues. For this research, the given description used for the BCI calculations could be of use in defining the input and output for the operational model.

2.6 HOUSING DEMAND IN THE NETHERLANDS

In the transition to a CE, starting new housing projects should be integrated within the goals to reach in the upcoming deadlines, such as the Paris Agreement in 2050. Materials and information about current stocks are present, but what is the future perspective of dwellings and the housing market? Multiple articles express the need for growth in housing in the future concerning the increase of population coming years, but also a change of demand in living environments compared to the dwellings build the last 80 years ago. Next, to the change in demand, the same articles express the concerns included within this ambition of the new dwelling projects. Van der Meulen (2018) expresses the problems within the growth of the dwellings capacity of the Netherlands. In 2017 70.000 dwellings are added, which is still not a significant growth to fulfill the needs of the growing population. At the moment there is a shortage of 246.000 dwellings in the Netherlands, which is 3.2% of the current housing stock. According to Van der Meulen (2018), if every year the same amount of dwellings is added to the housing stock, it will not conquer the growth of the demand for new dwellings because of the rising population. In the current speed dwellings are being constructed, multiple construction companies such as VolkerWessels, Heijmans and TBI predict not even half of the prospected dwelling will be built in 2030 (ANP, 2019). And is it even possible to reach this amount of growth of new dwellings? Because the government puts the responsibility of most of the large housing projects at most of the municipalities, which mostly lack of expertise, resulting in either too expensive projects without any idea of costs factors or quick and cheap production of standard dwellings, without any concern for municipal plans and integration with the surrounding area (Vermeeren, 2018).

2.6.1 GROWTH OF POPULATION IN THE NETHERLANDS

Prognosis shows that between 2017 and 2029 the population of the Netherlands will grow with approximately 697.000 households, which is 8,7% of the current households (Rijksoverheid, 2018). Table 2.1 represents the growth among the different types of households. The different prognoses still has a difference of approximately 300.000 households between the highest and lowest variant. The number of single households will increase the most, such as the people with the age of 65+ (Table 2.2).

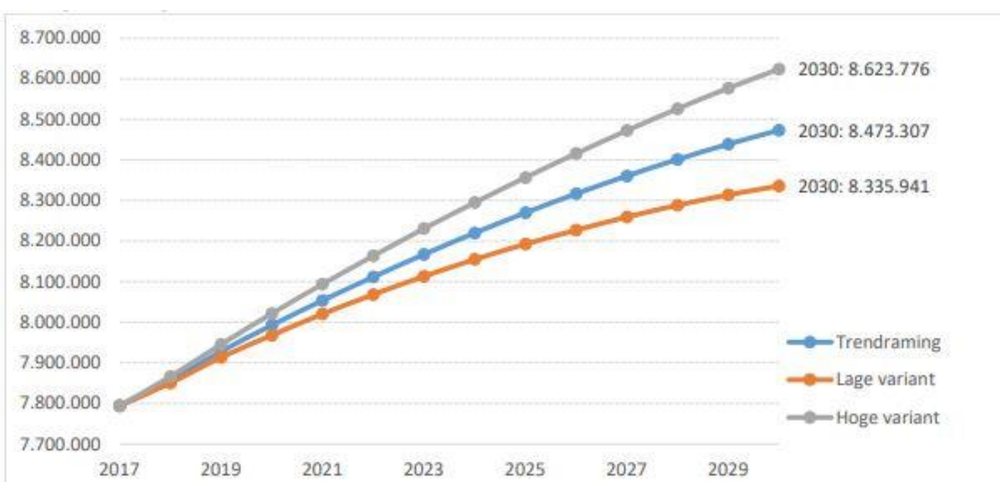


Table 2.1 Prognosis of the household size in the Netherlands in the period 2017 – 2030 (Rijksoverheid, 2018)

The predicted growth of population and households does not necessarily mean the demand for dwellings is equally divided over the country because the prognosis differs for each province. Especially close to the big cities in the western part of the Netherlands, the population in 2030 will have increased more compared to the northern and southern provinces. Figure 2.20 visualizes the percental growth of each municipality among the entire country in 2030 compared to 2015 (Rijksoverheid, 2018). This shows that the demand for new dwellings is at a higher level in certain provinces compared to others, looking at the near future of 11 years. These areas will, because of its higher demand for dwellings due to faster-increasing population, create multiple starting dwelling projects. The demand for a CE will create ambition for the new dwellings, to connect to the SDG's will have to be taken into account when developing and designing the new dwellings.

Households Configuration	**2017**	**2030**	**Increase 2017 - 2030**	**Procentual Increase 2017 - 2030**
Type				
Single	2.961.000	3.459.000	497.000	16,8%
Single parent family	562.000	589.000	27.000	4,8%
Living together with childeren	2.024.000	2.006.000	-18.000	-0,9%
Living together without childeren	2.206.000	2.372.000	166.000	7,5%
Other households	41.000	48.000	6.000	14,7%
Age				
< 30 years	950.000	962.000	13.000	1,3%
30 - 44 years	1.801.000	1.957.000	155.000	8,6%
45 - 64 years	2.926.000	2.669.000	-258.000	-8,8%
> 65 years	2.117.000	2.886.000	769.000	36,3%
Total households	**7.794.000**	**8.473.000**	**679.000**	**8,6%**

Table 2.2 Development of households in size and age, in the period 2017 – 2030 (Rijksoverheid, 2018)

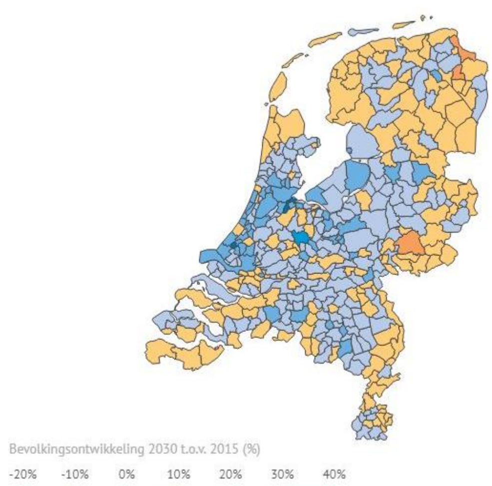


Figure 2.20 Bevolkingsgroei per gemeente, 2015-2030 (Centraal Bureau voor de Statistiek, 2016)

2.6.2 GROWTH OF DWELLINGS PROGNOSIS

The growth of the population will result in a growth in dwellings (Rijksoverheid, 2018). The overview by Rijksoverheid (2018) predicts, based on actual data about the current status of the dwelling stock and the demand for new dwellings because of the predicted growth of population, what the development of the dwellings stock will be towards 2030. Table 2.4 shows for every province of the Netherlands in how many dwellings the development possibly will result, while Table 2.3 shows the prognosis of the planned capacity when the demand and current stock are being put next to each other.

Provinces	Increase 2017 - 2030			Difference vs demand	
	Prognosis demand	Prognosis supply	Netto plancapacity	Prognosis demand	Netto plancapacity
Groningen	12.000	15.500	16.500	3.500	4.500
Friesland	11.000	12.500	15.000	1.500	4.000
Drenthe	10.000	11.000	14.500	1.000	4.500
Overijssel	25.000	27.000	23.000	2.000	-2.000
Flevoland	31.000	29.500	38.000	-1.500	7.000
Gelderland	65.000	69.500	77.500	4.500	12.500
Utrecht	77.500	75.000	81.500	-2.500	4.000
Noord-Holland	166.000	175.500	213.000	9.500	47.000
Zuid Holland	169.000	167.000	158.500	2.000	10.500
Zeeland	5.000	6.500	10.500	1.500	5.500
Noord-Brabant	92.000	104.500	119.500	112.500	27.500
Limburg	2.500	7.000	26.000	4.500	23.500
Total	**666.500**	**701.000**	**793.500**	**134.500**	**127.000**

Table 2.3 Prognosis on increase in dwellings needs, dwelling stock and plan capacity per province in the period 2017 – 2030 (Rijksoverheid, 2018)

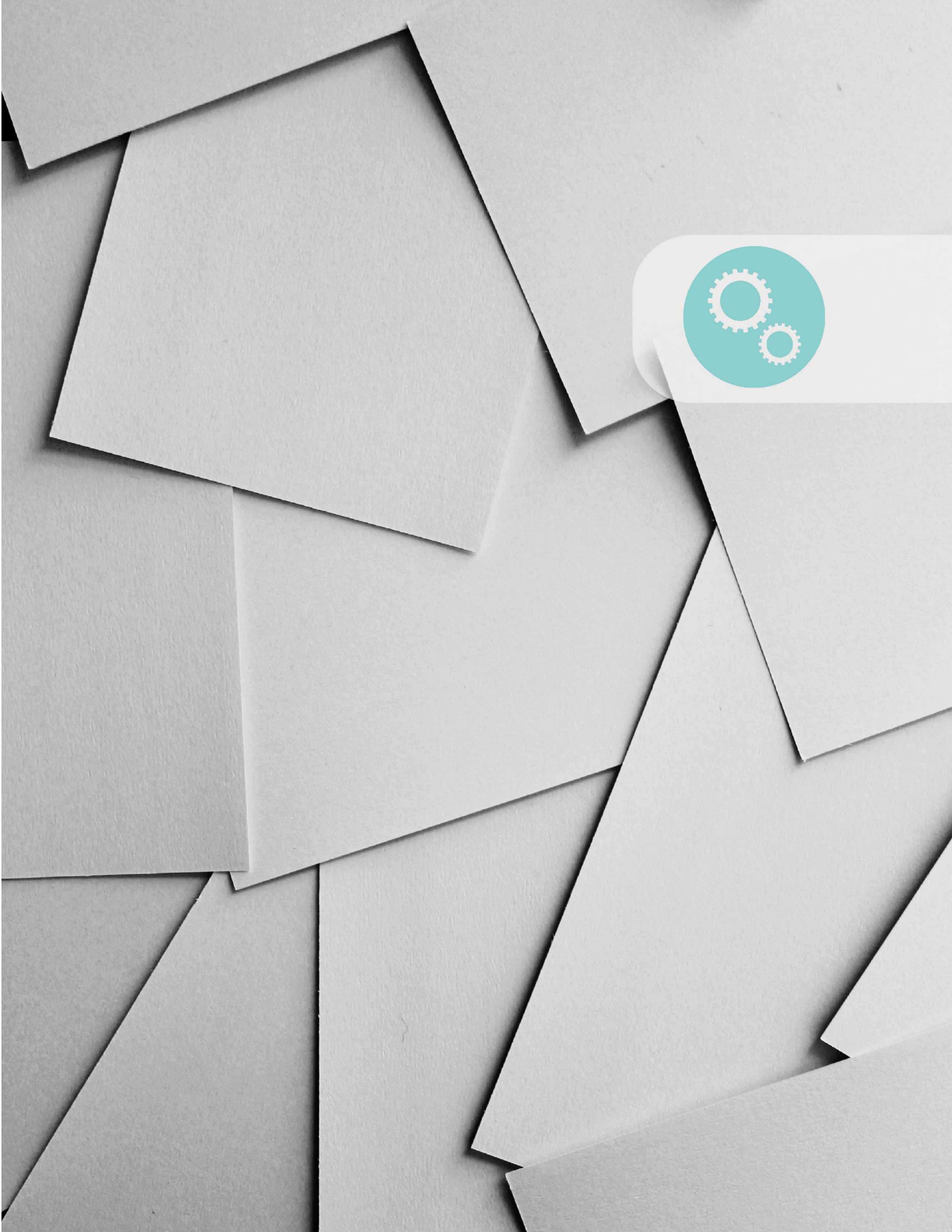
So we know that many buildings have to be developed in the near future to fulfil the housing shortage prognosis, but what kind of buildings are necessary for the future? Looking at the SDG's, most of the houses should be energy neutral, cut from natural gas and from a sustainable point of view developed. Multiple cities are already in the progress of redesigned current dwellings, which are poorly insulated and still running on gas. One of the cities is the capital Amsterdam, which aims to establish effective collaboration between the city and stakeholders which results in scalable, cost-effective building design that answers to the wishes of the residents of Amsterdam (Kanyemesha, 2017). Together with the residents, the questions are being asked what their potential living situation could look like and how to transform current dwellings and design new dwellings into neutral energy homes, within a feasible budget (Kanyemesha, 2017). Eventually, 100.000 new dwellings are the amount that is currently set as the goal for the project from Amsterdam Smart City, in combination with Alliander and Arcadis (Kanyemesha, 2017). This project shows an interesting example of how to tackle the challenges for the need of new dwellings, but still the motivation to keep the focus on developing energy-neutral homes and also the feasibility in costs and duration of the project. Eventually, this will result in residents and municipality joining the transition towards a CE.

Provinces	Supply 2017	New constructions 2017 - 2030	Deconstructions 2017 - 2030	Supply 2030	Development supply 2017 - 2030
Groningen	276.500	24.500	9.000	292.500	15.500
Friesland	296.500	19.500	7.000	309.000	12.500
Drenthe	219.000	15.000	4.500	230.000	11.000
Overijssel	497.500	40.500	13.000	524.500	27.000
Flevoland	164.000	30.500	1.500	193.500	29.500
Gelderland	888.000	85.000	15.500	957.500	69.500
Utrecht	554.500	89.500	14.500	629.500	75.000
Noord-Holland	1.307.500	208.000	32.500	1.483.000	175.500
Zuid-Holland	1.666.500	219.500	53.000	1.833.500	167.000
Zeeland	184.500	11.000	4.000	191.000	6.500
Noord-Brabant	1.104.500	122.500	18.000	1.208.500	104.500
Limburg	527.000	17.500	10.000	534.500	7.000
Total Netherlands	**7.686.000**	**883.000**	**182.500**	**8.387.000**	**701.000**

Table 2.4 Prognosis on development of the housing stock, in the period 2017 – 2030 (Rijksoverheid, 2018)

2.7 CONCLUSION

Looking at the current state of the construction industry, multiple factors are ready to innovate. Especially the rapid transition towards a CE, in which the construction industry should participate. There are already multiple platforms and construction companies that are making an attempt, but a fully integrated system within the construction industry is far from existing yet. The literature study shows that it is recommended for researchers of the construction industry to tackle the innovation step by step and research the factors that could be improved, concerning feasibility and efficiency, instead of trying to tackle the entire structure of the construction industry. A focus to improve a particular module of the entire system will result in follow up innovations, as a reaction to the development of smaller structures. The creation of the middle man would be a starting example, which could be used as a pilot within to construction industry and promote the possibilities of the rapid development. Systems already developed could connect within the transition and future starting design and construction projects could be realized, keeping the SDG's, sustainable demands and the CE in mind.



PART 3 METHODOLOGY

As mentioned in the first chapter, the construction industry should be aware of the innovation that is necessary to follow up the transition towards a CE. The goal of this research is to participate in the transition. The following chapter focusses on the explanation and elaboration of the methodology that is used for this research and how the research is executed related to the research questions and research goals, mentioned in section 1.2.3 and 1.2.4. This chapter also connects the conclusion and information delivered by the literature study to the research, which showed the gap in the literature and the possible business case of the missing middle man.

At first, the research setup is elaborated, explaining which methods are used. The next section focusses on the setup of the operational model, based on Barendse et al. (2012) and why the operational research method is applicable to the setup of the current research. The input of the model is provided by the current supply, on which is elaborated in chapter 3.3. The demand and output required for the operational model are explained in section 3.4, the feasibility in section 3.5. Finally, the execution of the model is elaborated and concluded, presenting the results of the model in chapter 4.

3.1 RESEARCH SETUP

The research started with the JIP, which is elaborated in section 1.1.3. Next, the execution of the main research and answering the main and sub-questions of this graduation proposal are conducted at Alba Concepts. In this section, the structure of the research setup as conducted are elaborated.

3.1.1 INTRODUCTION

The topic of reusing building materials and the transition towards a CE contains a lot of different aspects that could be of importance. The sub-questions alone are a combination of the conceptual model, providing multiple topics to be researched, before being able to answer the main research question. The different topics are researched by a conducted literature review, defining each subject that comes to the attention. This delivered an overview of theories developed together with the research question of this graduation project. The next step consisted of an exploratory analysis of the subject. The input for the model is delivered by the literature study and expertise of colleagues within the graduation company, during expert discussions. Eventually, the correct information is abducted in order to design the operational model.

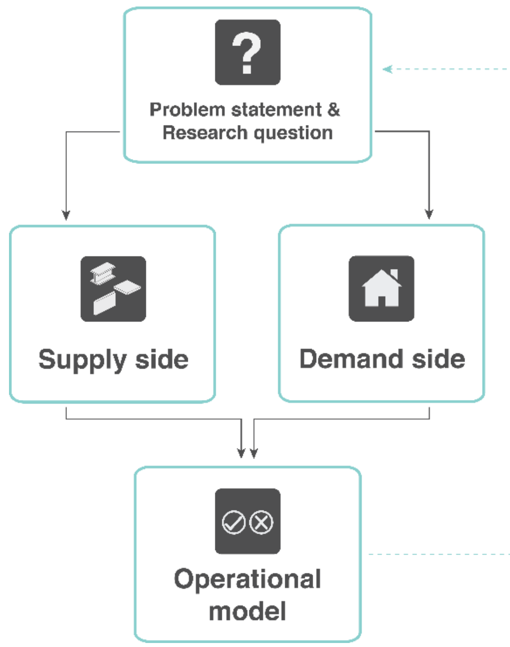


Figure 3.1 Research setup small (own ill.)

The JIP is involved in the research design as well, during the internship at Royal HaskoningDHV. The given business case of Groningen delivered a research subject, a set of datasets with information about example cases and other input necessary for the operational model. The setup and extended version of this model are explained in Appendix 11.2 and a representative dataset is visible in Appendix 11.1. Both the exploratory research and the research during the JIP period are compared and used as input for the operational model. To design the operational model, the exploratory research in combination with the JIP provided the problem definition, consisting of the objectives, the user requirements, the constraints, and the functions. This is necessary for the setup of the model (Dym et al., 2004). Eventually, the results from the operational model provide an answer to the main and sub-questions of the research.

Figure 3.2 shows an overview of the setup of the research. The main research question is focussed on how the supply of existing building elements and demand for new construction projects can be linked in order to reduce the use of virgin materials and thereby improve circularity in the construction industry. This is the starting point of the research, which has been developed during the orientating period within the JIP. The setup of the research is separated into two different research paths. The left path focussed on the supply side, which consists of several case studies. This supply, which is partly provided by graduation company Alba Concepts, provided a contextual situation on a certain level. As mentioned earlier by Koutamanis (2018) and in section 2.3, the possible levels of scale are project-based, region-based or enterprise-based. Every level of scale has a different set of case studies, which means different datasets and multiple projects. In section 3.3 the different case studies are analysed, the data is obtained and explained how they are connected to the operational model. This section also answers the first sub-question of the research.

The second route of the research setup model focussed on the demand side of the research question. For the variables of the operational model, certain program requirements are defined. This side consists of the conducted literature study of the subjects, such as urban mining, circularity, feasibility et cetera. On the other hand, expert discussions took place to provide information on the subjects coming from practice. It also provided arguments for the right demand for the program requirements. These two separate actions provided input for the operational model on the variables and helped answering the second sub-question.

Through multiple design stages, the operational model is analysed and tested. The goal of the operational model is to answer the main and third sub-question of this research proposal. The final design of the operational model is checked with the main research question through a feedback loop. The feedback provides information about whether the first or the second path needs to be adjusted, providing different input for the model, to reach a final, successful design that shows eventually if supply and demand fit and if it reduces the use of virgin materials. Through the feedback loop, the model is constantly updated and refined to create an optimal working design. This operational model is designed to apply in real-life cases for the stakeholders who are interested to reduce the use of virgin building materials in new projects. The conclusion of the qualities and possibilities of the model are discussed in chapters 5 and 6.

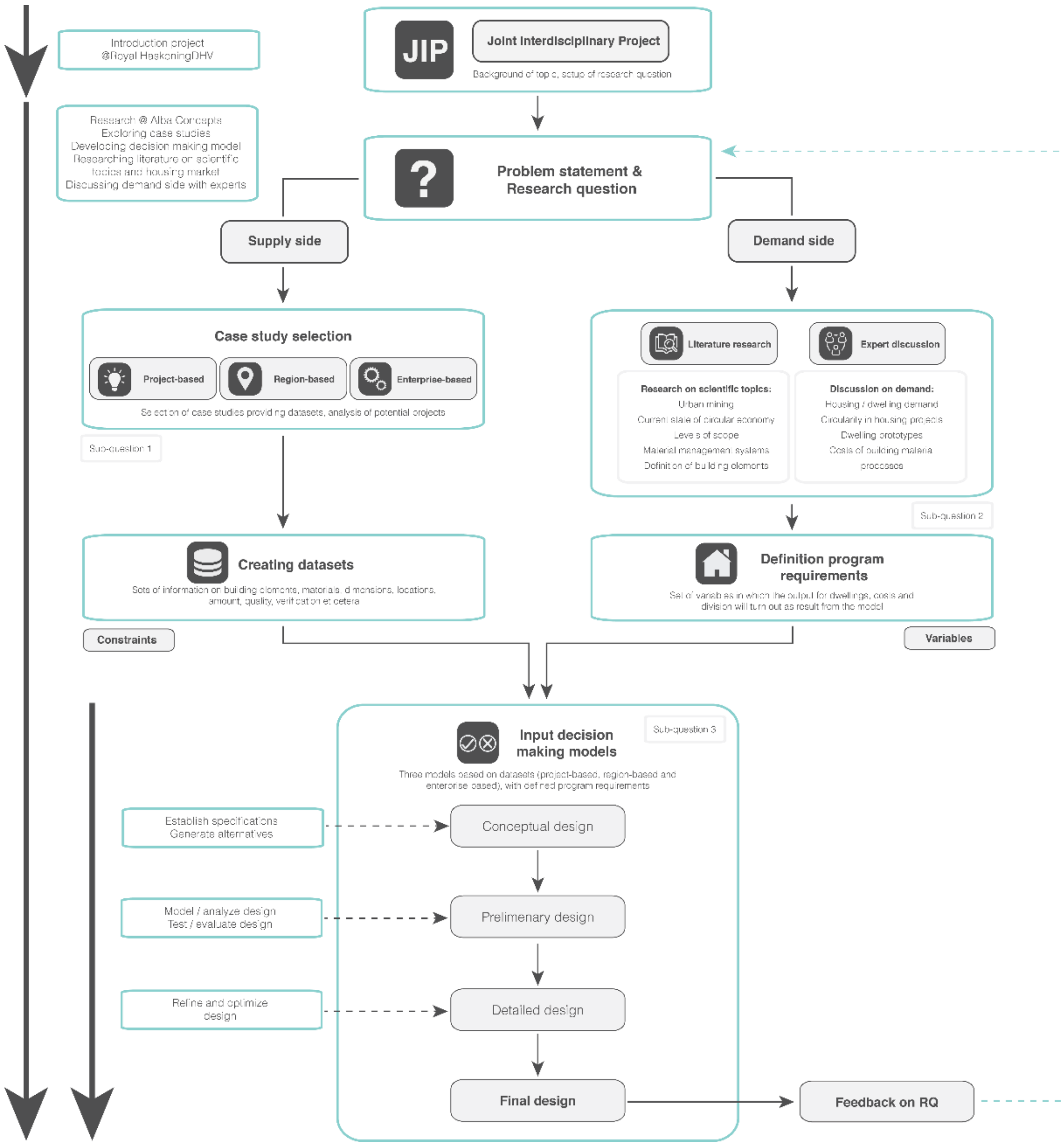


Figure 3.2 Research setup (own ill.)

3.1.2 EXPLORATORY RESEARCH

Even though the context of this graduation project consists of multiple popular topics in the construction industry such as UM and CE, there are still undefined subjects with multiple interpretations. These type of broad concepts are complex, open to all kinds of qualifications and whether or not the subject of UM will have any influence in the development of design and construction processes are questions yet unanswered. With the help of literature and field experts, these questions could be answered (Verschuren & Doorewaard, 2010). Therefore a qualitative approach is performed, existing of exploratory research. As well, the most prominent methods of data collection of qualitative approach are organisational research and unstructured or semi-structured interviewing (Bryman, 1989). The results from the exploratory research is used as input for the design research, which are elaborated in section 3.1.3.

The exploratory research is conducted in collaboration with colleagues of the graduation company Alba Concepts and the visitation of multiple conferences on circularity and CE. Through the exploratory research phase, information on different topics related to the graduation is researched and discussed with experts on the topic, creating a bulk of information that is used for design purposes. The multiple colleagues, which are specialists in the areas circularity, costs analysis, design, consultancy and the built environment provided knowledge as a base for further development of the research.

In relation to the discussions with experts and literature research, case studies are used as well within exploratory research. Case studies have often been viewed as a useful tool for the preliminary, exploratory stage of a research project, as a basis for the development of the 'more structured' tools that eventually is developed further on in this research (Rowley, 2002). This stage consists of the collection of data and the research for the housing demand in the Netherlands. According to Bryman (2012), the basic case study requires details and intensive analysis of the chosen cases. This means it will necessarily be a part of the supply side research, to figure out the constraints for a future decision-making model, based on the analysis and final decision on cases to use as input.

3.1.3 RESEARCH THROUGH DESIGN

The following section provides a concise definition of 'research through design' or 'design research', based on scientific papers and how design research is being operated in finding a solution for the typical research problems which is this graduation thesis. The most important aspect of research through design is that it seeks to provide an explanation or theory within a broader context (Frankel & Racine, 2010). It creates the possibility to solve complex problems, projects that could be defined as 'ill-defined' or 'wicked' (Rittel & Webber, 1973; Rowe, 1991). Such complex problems are difficult to explain and often formulated in a different sense, which makes it complicated to predict a solution in advance. With the help of designing a solution space, it creates the possibility to define the research problems in a more constrained area, narrowing down the context to integrated solutions (Nijhuis, de Vries, & Noortman, 2017). For this graduation research, creating design research provided the eventual solution space to solve the main research question.

Based on Van den Akker, Gravemeijer, McKenny, and Nieveen (2006) literature of multiple design research authors shows 5 different characteristics, related to this type of research:

- Interventionist: the research aims at designing an intervention in the real world;
- Iterative: the research incorporates a cyclic approach of design, evaluation and revision;
- Process-oriented: a black-box model of input-output measurement is avoided, the focus is on understanding and improving interventions;
- Utility oriented: the merit of a design is measured, in part, by its practicality for users in real contexts;
- Theory oriented: the design is (at least partly) based upon theoretical propositions, and field testing of the design contributes to the theory building.

These 5 characteristics show the qualities of the yet to be developed operational model, which is explained in section 3.2 and creates a setup of how to answer the problem stated in the research question. The goal of this research is to eventually propose and advice on how in the real world the use of virgin building materials could be reduced. The research questions also propose a comparison between supply and demand to make this happen. This creates a possible solution space, which could be reached by the development of the tool.

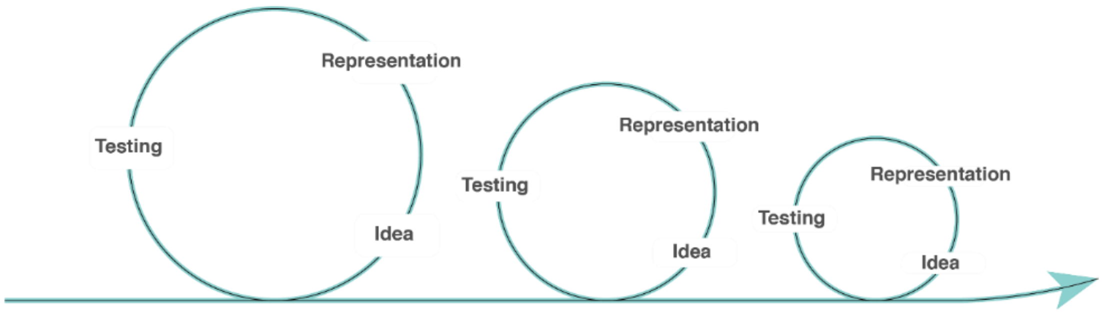


Figure 3.3 Cyclical process of the development of idea's, based on Van den Akker, Bannan, Kelly, Nieveen, and Plomp (2013)

The design process to achieve the characteristics mentioned by Van den Akker et al. (2013) can be accomplished throughout operational research. Figure 3.4 shows the 8 steps of the development of a particular research process (Kumar, 2011), which is used in operational research and shows the essence of combining the theoretical research steps with practical development of an operational model, to eventually produce a binding research report. The design process of an operational model is shown in Figure 3.5 by Dym et al. (2004). Combining these two schemes of a design and research process is essential in resolving operational related complex problems, such as the main research question proposes. During the process, design research is always being further developed, while new ideas and proposals are being further evaluated in every phase. This creates a cyclical process, where every cycle starts with an idea, which is represented, tested and evaluated (Figure 3.3). The proposed design goal is the main objective, but because of the cyclical process, the final design solution is adjusted towards a different angle, due to the process of designing and generating new knowledge and insights on the subject. Thus the final design would be of a different context, compared to the proposed results at the beginning of the design research (Van den Akker et al., 2013). The cyclical process of research through design is an important tool to develop models for complex research problems. It gives the author the possibility to reflect on earlier work and look from different perspectives over different moments in time at the progress of the research. Eventually the products of design-related research consists of thoroughly reflected characteristics, compared to common research techniques. The following chapters show the adaption of design research in the operational model development and final results, which provides the feedback loop to the main- and sub-research questions.

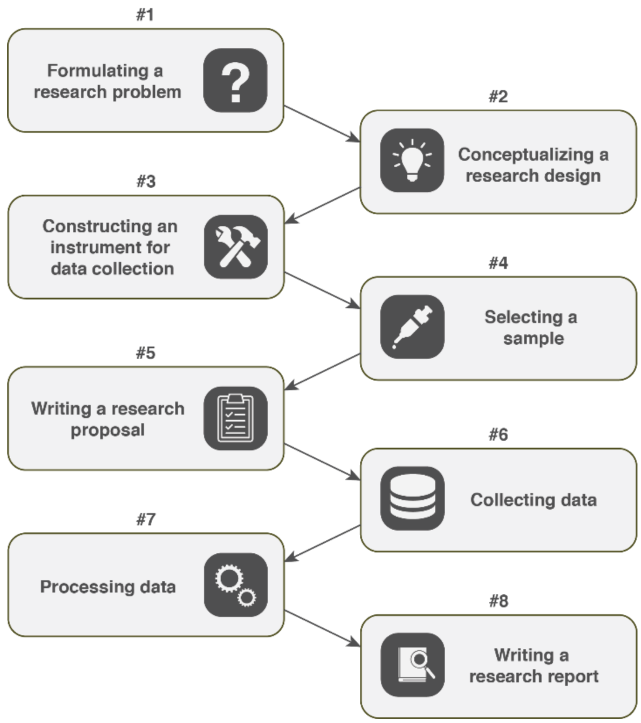


Figure 3.4 Steps of an empirical research process (Kumar, 2011)

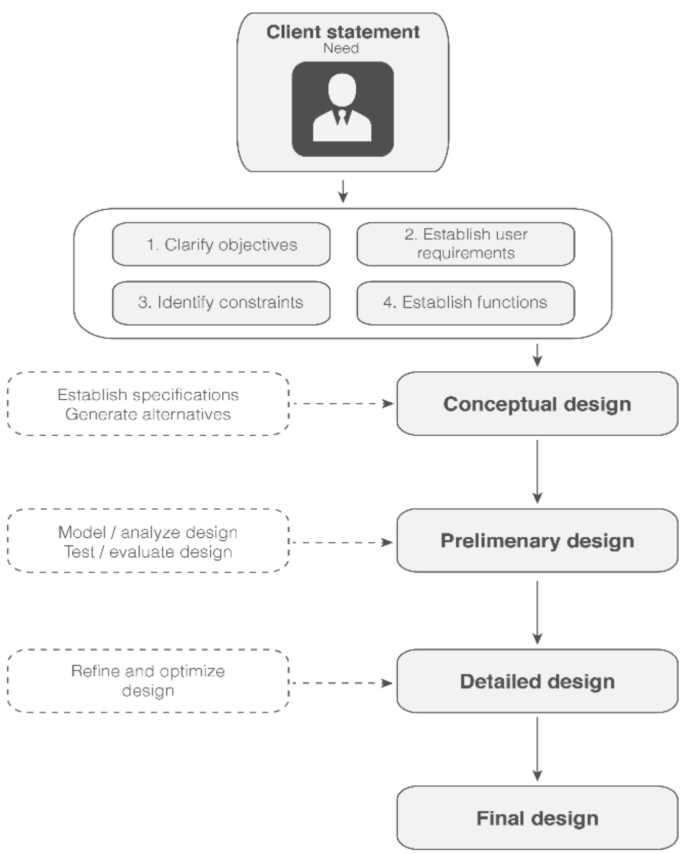


Figure 3.5 Steps of a design process (Dym, Little, & Orwin, 2004)

3.1.4 STUDY LIMITATIONS

Possible study limitations within this research could be the dependence on the motivation for third parties to refuse to collaborate in sharing datasets. To make it possible to test the business case of this thesis, it is important that there is information available coming from practice, to be used as a test case. Different companies and universities are in possession of information about certain waste flows and available building materials but are contractually bound to privacy on the specifications of these datasets. Mostly, companies and platforms that gather and assess these datasets have a contractual agreement, which states the procedure on how to collaborate and communicate with third-party stakeholders. This is because there is still an open market around this upcoming subject, which creates competition and the need for protecting the information of the adjoining companies. To create the decision-making tool for this research, there should either be parties involved that are not participating within the competition and are open to sharing datasets, or there should be a clear Non-Disclosure Agreement (NDA) between the companies and the Delft University of Technology on how the thesis is being reported and structured. When there are clear agreements on how the presenting functions, the datasets could be shared and the business model could be tested within the practice.

3.2 OPERATIONAL MODEL

Besides the literature research and the expert discussions, a part of this graduation research contains designing an operational model or decision-making model. Operational research deals with operation-related problems, specific research that starts with a typical 'how to' question. It deals with design problems, research about new artefacts that do not yet exist. The goal is to improve a certain subject or topic through designing the operational model and improving the model by running it, again and again, creating a detailed final design (Barendse et al., 2012). This research provides a model, which uses linear programming to determine what the most optimal solution is, concerning the research goal. Within this research, the model calculates what combinations of dwellings maximizes the use of already available materials, directly minimizing the use of virgin building materials (Binnekamp, 2018). The difference in costs between the dwellings designed with reusable building materials is compared with dwellings built completely with virgin materials. Eventually, this generates results, creating overview and an advice for stakeholders whether or not executing reusing materials will improve the circularity of their project. The model is adaptable to different contexts, by upscaling or downscaling the setup and adjusting the variables and constraints. A schematic overview of the model is presented in Figure 3.6.

The input for the model is provided by an additional analysis of certain case studies. The case studies are used as an empirical inquiry that investigates a certain topic such as UM within its real-life context, especially when the definition of the phenomenon UM is not clearly evident. In other words, the case study covers the conditions of the context given, related to the study of UM (Yin, 2014).

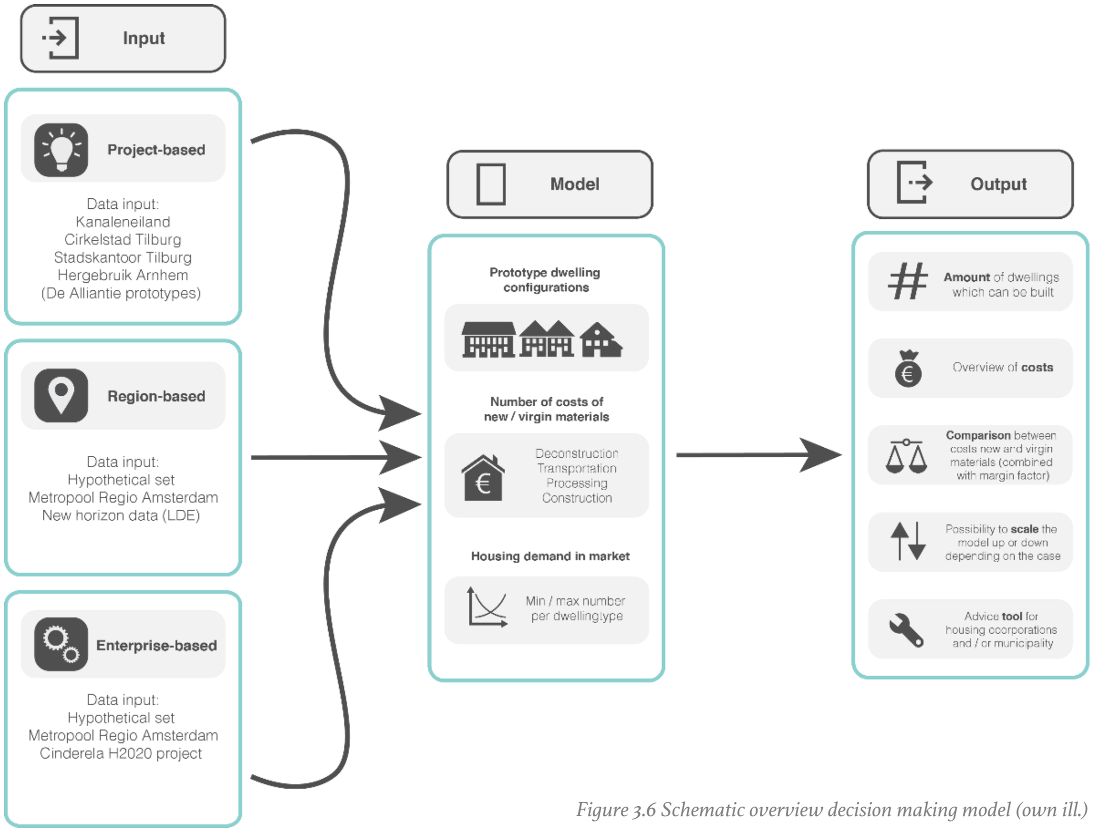


Figure 3.6 Schematic overview decision making model (own ill.)

The following section explains the setup of the concept of operational research and the creation of the model, which helps to answer the research main- and sub-questions of this thesis. First, the specifications and the methods that substantiate the setup of the model are elaborated, divided into three chapters: First the input for the model, describing the variables and constraints that are necessary to set the boundaries of the different models to be developed. Next, how the model runs its operations. In this chapter, the 'What'sBest!' add-in, which performs the calculation and the formulas behind the module, showing how the operational model can operate within Microsoft Excel is presented. The output is elaborated next and why this is necessary to determine before starting the calculation. Finally, the execution of the models are highlighted.

3.2.1 SETUP

For the operational model to be developed, multiple criteria should be determined in which the operational model performs. A set of constraints and variables provide the limitations of the model, which are part of the input. The model runs on the 'What'sBest!' add-in for Microsoft Excel, in combination with a linear programming (LP) model. The final output is determined by the constrictions and the demand coming from stakeholders. A schematic overview of the three phases is shown in Figure 3.7 and are elaborated in the next sections. The goal of the decision-making tool is to find the most optimal solution for a certain operation related problem set of variables, depending on the constraints given by a certain context. During the JIP at Royal HaskoningDHV, explained in section 1.1.3, the basic setup of the model is developed. An example of what the datasets look like, which are used during the JIP, is presented in Appendix 11.1. It shows a 3D image (BIM model), the different type of building elements (walls, floors, beam, etc.) consisting of a certain material (bricks, steel, wood, etc.) and the quantity of that type of building element. A larger explanation of the model is shown in Appendix 11.2.

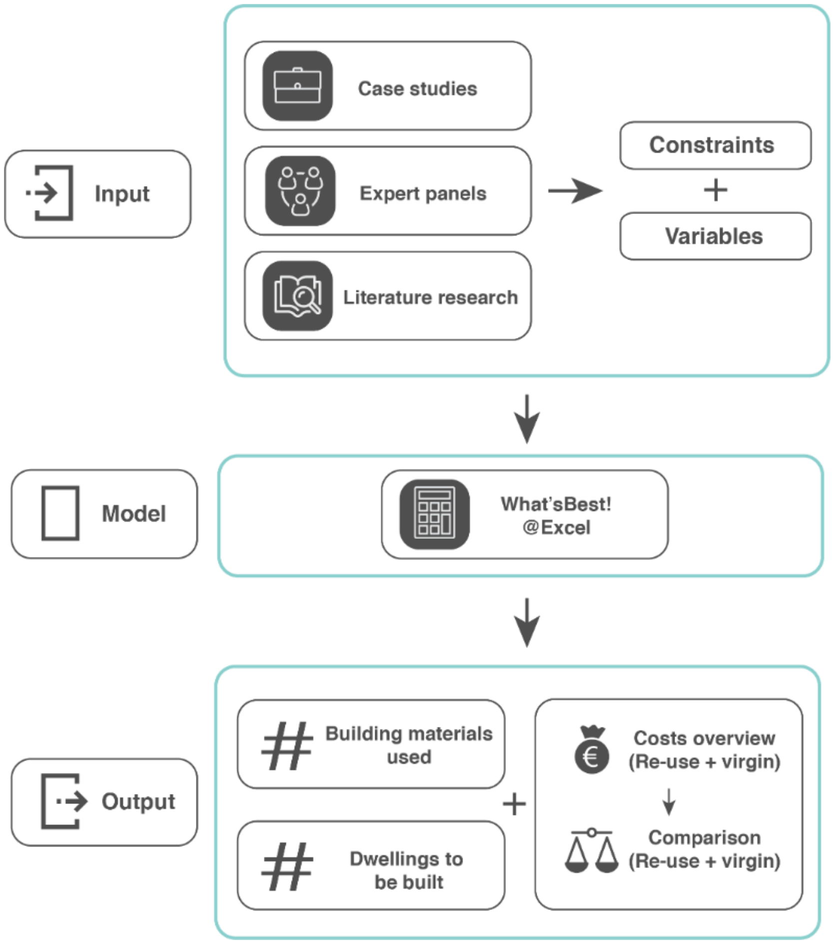


Figure 3.7 Schematic overview three phases of the operational model (own ill.)

When the scope of an operation related question is larger, the amount of constraints and variables is more extensive as well. It increases the number of possible solutions. This example model functions as an expansion tool of the usage of the materials and data available. It generates an output where for example an organisation such as the municipality of Groningen could have a lot of use of, discovering the possibilities with the materials of the current housing available, depending on the quality the new type of dwellings will be. Also, a collaboration between contractors (which could retract the materials from the buildings) and architectural firms (designing new dwelling types) could be improved with the help of this model. In this context, the model is used from a region-based perspective. However, small changes in the model could provide a working system for a project- or enterprise-based context. In each case, the model proves if the reduction of virgin materials and the improvement of circularity in design and construction projects are succeeded.

The following section explains the entire setup of the model and the mathematical theory behind the structure. The input, model and output specifications are highlighted and adjusted to the three different levels of scale.

3.2.2 INPUT SPECIFICATIONS

As is mentioned in the introduction of this thesis, it is necessary to rethink the structure of construction projects and use different databases. The number of materials that are available in our world is limited, to reuse materials from dwellings that are no longer in use is the way to go. These dwellings could be found in case studies related to this subject and available by external parties or the graduation company Alba Concepts for this thesis. These datasets act as input for the operational model, but existed of different sets of materials that could be used. In section 3.3 it is shown which datasets are used for the models and of what type of information the datasets exist of.

This section explains the different type of information used and how the information operates in the model. Figure 3.8 shows which type of information is used to define the variables and the constraints possibilities of a typical model. These constraints and variables are explained in section 3.2.2.2 and 3.2.2.3. The case studies are as mentioned provided by third parties. The discussion takes place with experts in the area of circularity and UM. The literature research provides information on how to determine which techniques are already used and how specifications of datasets are defined and validated, such as the disassembly module.

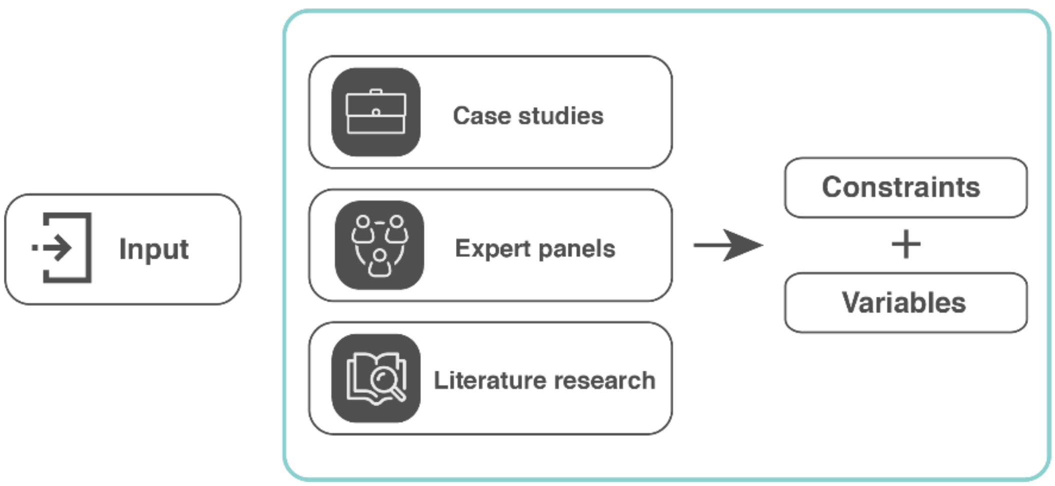


Figure 3.8 Schematic overview input (own ill.)

3.2.2.1 DESIGN SPACE

Creating a perfect connection between supply and demand requests an optimal configuration of the different elements. When a design has to be made, it is very time-consuming to research and develop every possible concept of the design, which is not efficient and could be performed in another way. Barendse et al. (2012) proposes a design methodology in operations research, where the alternatives to be evaluated are not known a priori. Barendse et al. (2012) uses the concept of 'design space', described by Dym et al. (2004):

'A design space is a mental construct of an intellectual space that envelops or incorporates all of the potential solutions to a design problem. As a broad concept, the utility of the notion of design space is limited to its availability to convey a feel for the design problem at hand. The phrase large design space conveys an image

of a design problem in which (1) the number of potential designs is very large, perhaps even infinite, or (2) the number of design variables is large, as is the number of values they can assume.'

This space is defined by a combination of design attributes (variables) and constraints, with defined goals and objectives by the interested stakeholders, to help in the optimization process. The design space creates an area where the most optimal design alternative for the specific problem could be found, by a combination of the different variable values.

3.2.2.2 EXOGENOUS AND ENDOGENOUS VARIABLES

To design a decision-making tool, variables and constraints are decided. The design variables are design attributes. When designing a building, the design variables could be the buildings lettable floor space, a number of floors or the ratio between lettable and gross floor space (Barendse et al., 2012). There are different types of variables within the design space. The input variables, for example, the demand for a certain number of dwellings to be built, may be referred to as parameters, or exogenous variables. These variables cannot be controlled and are referred to as X_i.

The decision variables, the variables that can be controlled by the developer, are called the endogenous variables (Barendse et al., 2012). These variables are the results from the calculation and are determined by the exogenous variables and the restrictions made by the constraints, goals and objectives of the stakeholders. These variables are referred to as Y_i, they are given, determined from the context and are immutable as far as the decision-maker is concerned (Barendse et al., 2012). An example is the Groningen case, where the materials available define the endogenous variables. Datasets that are available provide a number of building materials to use for the case. Depending on the case, if the input is different, the endogenous variables could be different as well. These variables are necessary to develop the formula that is the foundation of the calculation method, which are explained in section 3.2.3.1.

3.2.2.3 CONSTRAINTS, GOALS AND OBJECTIVES

The constraints ensure restrictions and limitations within the decision-making model. The design is created by the constraints. For example, a client could decide how much of a certain material should be used, or how many dwellings of a certain type should be built. Also, a maximum of certain materials that are available is a constraint for the model. Without constraints, there would be no solution. The goals and objectives within operations research have a different meaning. Zeleny (1982) describes the conceptual and technical differences between constraints, goals, and objectives:

'A constraint is a fixed requirement which cannot be violated in a given problem formulation. Constraints divide all possible solutions (combinations of variables) into two groups: feasible and infeasible.'

'A goal is a fixed requirement which is to be satisfied as closely as possible in a given problem formulation.'

'An objective is a requirement which is to be followed to the greatest extent possible (either by minimization or maximization) given the problem's constraints.'

Within decision-making models, there are two different kinds of restrictions, referred to as constraints. The first consists of a minimum or maximum (or both) limitations for the amount of a specific variable. For example, when designing a certain dwelling with concrete walls, the restriction of how many concrete walls to use can be a constraint. This constraint is determined by the case studies, which provide input for the model. Often this number is more than zero. The input is the number of concrete walls that are available, accessible and of a certain quality, well enough to be reused. These types of constraints are called non-negativity constraints. On the other side of the model, there are the functional constraints, which represent the total usage of a particular resource, such as the number of brick walls that are in total accessible within the case. (Barendse et al., 2012). The goals and objectives support the decision whether or not the model fulfils the wishes of the client and tries to follow the requirements as much as possible, defined by the constraints.

3.2.3 MODEL SPECIFICATIONS

When the input is defined by the context of the case and the constraints for the model are set, it is important to create the calculation model. What is noticeable within Figure 3.9 is the importance of the 'What'sBest!' add-in in Microsoft Excel. The following sections explain the procedure within this add-in tool and elaborate on the mathematical background that supports the 'What'sBest!' add-in.

Figure 3.9 Schematic overview model (own ill.)

3.2.3.1 OPERATIONS RESEARCH FORMULA

Looking back on section 3.2.2.2, the variables can be defined as the exogenous and endogenous variables. The relationship (f) between the endogenous variables (X_i) and the exogenous variables (Y_i) can be determined by U. This represents the utility of the system's performance and is presented in the following formula (Ackoff & Sasieni, 1968):

$$U = f(X_i, Y_i)$$

To explain the formula and the utility of the system, the case of Groningen is used as an example. As mentioned in section 1.1.3, if new buildings in Groningen would hypothetically be developed, the goal would be to reuse the maximum amount of available building materials. As described in Appendix 11.1, data of structural elements from a single dwelling consists out of floors and walls. The materials used for this dwellings differ between bricks (M_b), concrete (M_c), steel (M_s) and wood (M_w). If there are multiple of the same dwellings available to reuse, the formula to maximize the total amount of materials (M_t) out of the four different types of materials mentioned are as followed (Binnekamp, 2018):

$$M_t = M_b + M_c + M_s + M_w$$

The exogenous variables (X_i) in this example case are the dwellings eventually to be built. This amount is decided by the demand of the stakeholders. As explained in Appendix 11.2, three different dwelling prototypes are developed. In section 3.4, the demand is researched and designed. For this basic example, the different dwelling types are acknowledged as A, B and C (N_A, N_B *and* N_C) (Binnekamp, 2018).

The endogenous variables (Y_i) cannot be controlled by the designer, but are based on the context of the case. If the dwelling type shown in Appendix 11.1 is existing of a certain amount of materials and if there are a certain amount of the same dwelling types available, the endogenous variables are a given amount. To create the three new type of dwellings, there should be a design that shows the required amount of building elements required to build the three different dwellings. This amount is determined by the stakeholders who are responsible for the demand. To explain the formula, Figure 3.10 shows the relation between the different dwellings, the available building elements and the number of elements necessary to create the 1 prototype of a particular dwelling. So prototype N_A requires b_A number of bricks, c_A number of concrete blocks et cetera. To define the total amount of bricks necessary (M_b), determined by the number of dwelling types (N_A, N_B and N_C) and the required amount of bricks of each type (b_A, b_B and b_C), provides the following equation (Binnekamp, 2018):

$$M_b = b_A * N_a + b_B * N_B + b_C * N_C$$

This goes also for the total amount of concrete, steel and bricks. Therefore the total amount of materials used is the sum of these 4 modules, as mentioned in the second formula.

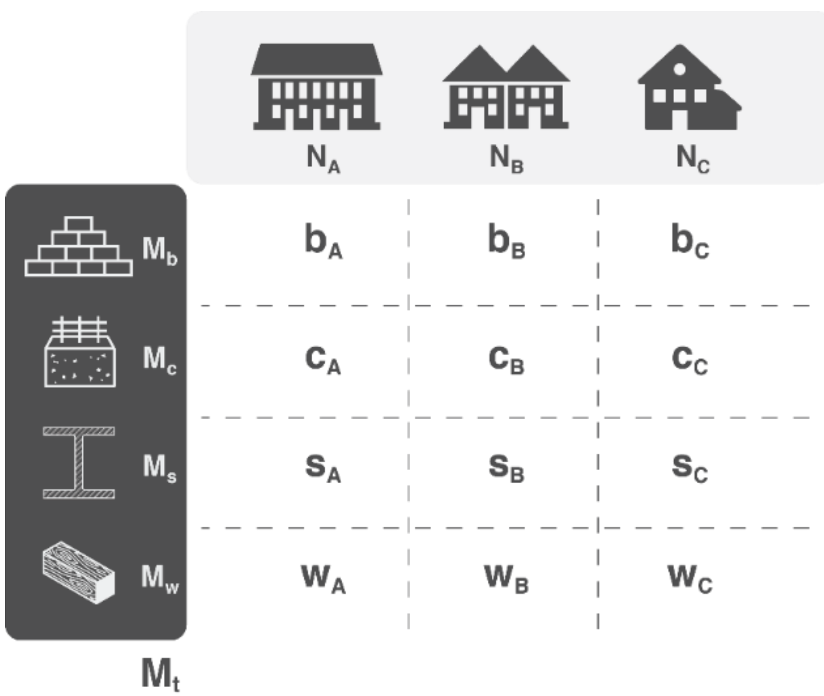


Figure 3.10 Mathematical overview endogenous variables (own ill.)

3.2.3.2 LINEAR PROGRAMMING GENERAL MATHEMATICAL MODEL

The case at hand is a general linear optimization problem. There is a request to search for the most optimal solution, with given constraints decided by the context. The mathematical modeling technique of linear programming helps to find the most optimal solution, given an objective function and a set of constraints (Barendse et al., 2012). This technique is often used in design methodology and also the 'What'sBest!' add-in is designed to solve LP problems. These problems are often real-life problems formulated into a mathematical model. The best solution for a certain objective is chosen by the process of LP (Kashyap, 2017). According to Kashyap (2017), LP is a simple technique where we depict complex relationships through linear functions and then find the optimum points. Depict is an important word, because even though LP solves real-life problems, but they are very complex and in LP, these relationships are simplified to linear relationships.

In traditional LP, the constraints such as b_A are considered to be fixed. Often they represent physical constraints that indeed cannot be changed, such as a number of building elements located in artifacts such as dwellings we no longer use. In Open Design (Binnekamp, van Gunsteren, & van Loon, 2006) the constraints are considered to be negotiable. This is a fundamental difference with traditional LP, which means that in practice if the mathematical outcome is infeasible, it can be changed into feasible after all (Barendse et al., 2012).

There are multiple online solvers and techniques available to find a solution for the different mathematical problems in real-life. For this thesis, the 'What'sBest!' add-in of Microsoft Excel is applied.

3.2.3.3 'WHAT'SBEST!' ADD-IN FOR MICROSOFT EXCEL

The 'What'Best!' add-in needs certain input and a definition for the output. When all the data has been implemented in the Excel sheet, the 'What'sBest!' add-in automatically finds the optimal solution for the division of materials used at the input side, as well as the optimal division of the output. As mentioned before, the model used the mathematical modelling technique of LP. 'What'sBest!' combines the proven power of linear nonlinear quadratic quadratically constrained second-order cone semi-definite stochastic and integer optimization with Microsoft Excel (LINDO Systems inc., 2019). The tool is clearly designed, with an interface that can be used by everyone who is capable of working in Microsoft Excel. The modelling is fast and easy, it is free of charge and can adopt large scale spreadsheet within the calculation. Every spreadsheet created partially with the 'What'Best!' add-in is designed with a 'solve' button, automatically running the model and creating a feasible or non-feasible solution, according to the case at hand.

Figure 3.11 Operational model schematic representation 'What'sBest!' add-in Microsoft Excel (own ill.)

The add-in creates adjustable cells in the top bar. These can be adjusted by the add-in in the quest for a solution. Looking at the literature, these cells are the endogenous variables (Y_i). There also has to be a cell defined as the 'Best!' cell. This represents the results of the maximum or minimum amount of materials used (M_t), depending on the demand of the research topic. The add-in only allows one cell to be maximized or minimized. This cell is the objective function of the model. Finally, the constraints in the model have to be defined. They enforce the restrictions of the model and are easily accessible within the program (Barendse et al., 2012). Figure 3.11 shows a schematic representation of a conceptual model, with the Groningen case used as an example to define the input and output.

3.2.4 OUTPUT SPECIFICATIONS

In operations research, specifically in the 'What'Best!' add-in of Microsoft Excel, the model creates, based on the input and the given constraints, a certain output. This output differs for each case. The output is generated by a solver of an LP related problem. It is very important the model works, the formulas are entered correctly and the different constraints are defined in a correct matter. By pressing the solve button it generates a solution of the model. Because the input has been limited so far in this example, the results are limited. Given an optimization variable in the model, the solution becomes more complex and creates different possibilities, trying to get the variable maximized or minimized. When there are more variables entered, it means the factors that affect the solution space will grow, not necessarily meaning there are more solutions, but better substantiated. Only when different variables are added, it creates more different types of solutions, connected to a variety of variables.

Looking at the example of the Groningen case and the setup for the following research of this thesis, the output of the example decision making model consists of the following subjects, visible in Figure 3.12: (1) the amount of building materials used from the input of the case studies, (2) the amount of prototype dwellings that could be built with the given datasets and (3) an overview of costs combined with a comparison between prototype dwellings constructed with reusable materials and virgin materials. To generate these numbers, the case input has to be defined by the case studies and the prototypes of the dwellings to be built have to be defined in materials, size and costs. Sections 3.4 and 3.5 elaborate on the setup of the demand and the feasibility.

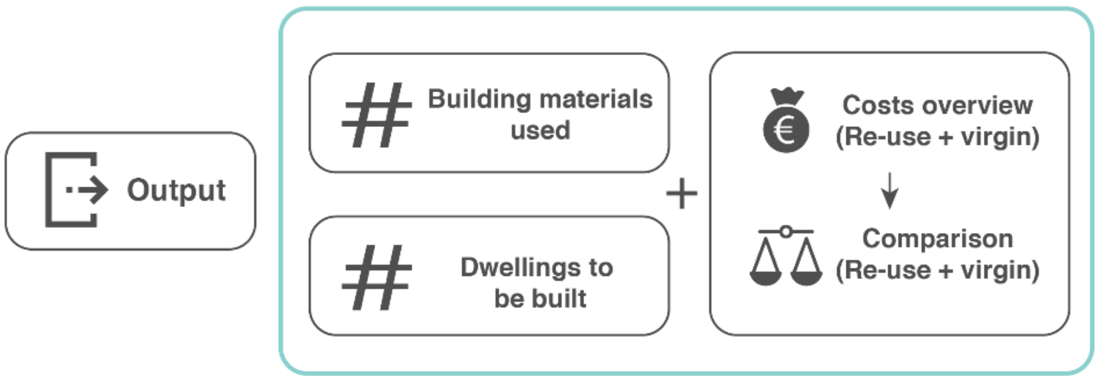


Figure 3.12 Schematic overview output (own ill.)

3.2.4.1 STAKEHOLDERS

The output should be determined by collaborating stakeholders. The development of the decision-making model could be of help to combine the wishes of multiple stakeholders related to a certain region or enterprise, acting as the middle man and improving the process of reusing materials between different organisations. It is important for the business case of the model to have as many organisations as possible involved in the process. As mentioned in section 1.2.2, if the information of accessible building materials and demand in housing projects is not shared, it creates more difficulties to empower the transition towards a CE, specifically in dwellings projects. Thus, the importance of sharing information and creating a clear overview of demand could accelerate the process. A further elaboration of the role of stakeholders is presented in section 3.4.3.

3.2.4.2 COMPARISON OF FEASIBILITY FACTOR

The main research question of this thesis is focussed on how the supply of existing building elements and demand for new construction projects can be linked in order to reduce the use of virgin materials and thereby improve circularity in the construction industry. The comparison is of importance in answering the main research question, by creating insight in whether or not reusable building materials are cheaper compared to virgin building materials. This will help to generate the first steps to substantiated results. The feasibility of the results is of importance when considering realizing projects with reusable materials. The margin of difference between the virgin dwellings and the reused dwellings determines whether or not it is feasible for an organisation to initiate reusing materials. On the other hand, if the margin is acceptable (less then or similar to 0%), it results in multiple interesting organisations to create dwelling projects with reusable materials, automatically stimulating the market secondary raw materials, but also cheaper deconstruction techniques and innovation on tools for reusable materials. The comparison is based on factual expenses on factors such as transportations, construction, deconstruction et cetera. In section 3.5 the numbers on feasibility are presented.

3.3 SUPPLY

Operations research focusses on finding a solution for questions starting with 'how to'. Mostly, these types of questions are linear programming problems, based on a mathematical model of a real-life case. To research problems from real-life, data is necessary coming from a context. As mentioned in the research design in section 3.1 and in multiple other sections, case studies are used as input for the operational model, to determine the supply side of the model and making the connection to real-life problems by implementing data from real-life cases. According to Bryman (2012), a case study entails the detailed and intensive analysis of a case. Within case studies, it is possible to use a single- and multiple-case study designs. For this research, multiple case studies are applied. The context of these case studies are the input of the operational model. It is necessary to define the level of scale on which the possible outcome of the model is based on. The organisational level of the case is key. The possibilities are divided into three different levels of scale, as explained in section 2.3: Project-based, enterprise-based or region-based (Koutamanis, 2018). The decision on which level what kind of model are executed is depending on the available datasets and whether this is realistic or not. However, it is also depending on the demand, which are elaborated in section 3.4.

The input for the model, existing of building information datasets extracted from case studies, are provided by multiple different companies. During this graduation, the gathering of information turned out to be an interesting struggle. Multiple companies and organisations are in the possession of usable datasets. But, as mentioned in section 1.2.2 the construction industry has trouble creating transparency between stakeholders, which are the same struggles that happened during the data gathering. Due to privacy regulations, trust problems and an incomplete overview of substantiated arguments, sharing information and sharing datasets for study-related research were not always possible. This is why the data used within the three models are sometimes incomplete and sometimes hypothetical, based on estimations or public figures. The graduation company Alba Concepts provided a sum of projects, which are evaluated and checked whether or not they can be used as example cases to test the conceptual model.

Figure 3.13 Cinderela project conference Amsterdam (Pranjić & Mladenović, 2018)

Also, during the internship, a number of conferences have been visited to connect with interesting parties on the CE. In Amsterdam at the Advanced Metropolitan Solutions Institute (AMS), a conference was held on the H2020 Cinderela project (Figure 3.13), discussing the possibilities to create new CE business models for more sustainable urban construction. This conference was a collaboration between the Delft University of Technology, AMS and KplusV. During the Circular Economy Festival in the city of Nijmegen (Figure 3.14), many companies were joining, discussing the challenges to face to transform to a CE. These conferences connected different initiators of the CE development and provided new ideas and goals that could be reached together.

Figure 3.14 Circulaire economie festival Nijmegen (Vonk, de Jager, & Dirkx, 2019)

3.3.1 DATASETS STRUCTURE

Operational research tries to solve complex problems based on real-life context. This given context should provide the correct information that could be used to test the model developed so far and create a realistic result that could provide advice for interested stakeholders. This supply could exist in many different structures and quantities. This section provides information on the different possible datasets that could be used for models in the different scale levels, described in section 2.3. As explained by Bryman (2012), a basic case study entails the detailed and intensive analysis of a single case. To use the correct data from a context a basic case studies analysis is necessary to create a

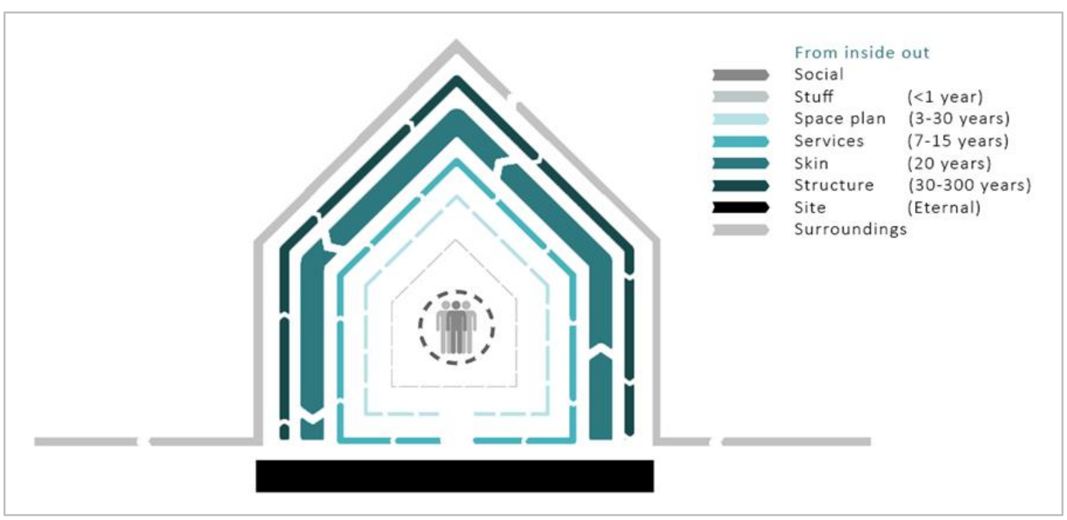


Figure 3.15 Shearing Layers (Brand, 1994)

database, in order to eventually use the datasets as input. Many information sets could consist of an overkill of data, which makes it necessary to limit the analysis to the primary data, to use as input for the model. The shearing layers dwelling structure designed by Brand (1994) (Figure 3.15) is an excellent reference to limit down the datasets to the necessary building materials for the operational model. The six different layers (Stuff / Space plan / Service / Skin / Structure / Site) with each different lifespans are well-known criteria in the circular construction industry world. For this research, the materials used for the model and collected from the datasets consists of the 'Skin' and 'Structure' layers, mostly structural and external materials. Due to the shorter lifespan of the other layers and the less information available in the chosen datasets, the other layers are left out within this calculation and preserved for future research possibilities, which are discussed in section 5.2.

Next to the chosen layers of Brand (1994), the datasets should consist of the following criteria, in order to provide sufficient relevant data in a clear dataset overview, as visible in Figure 3.16.

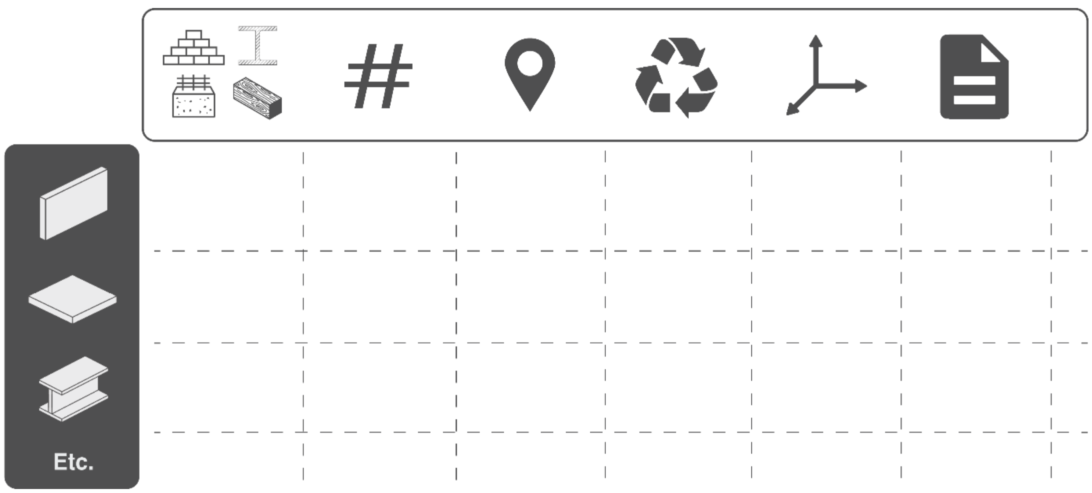


Figure 3.16 Database structure (own ill.)

Type of building materials (horizontal)

Depending on the context, it should be clear what type of materials are included within the datasets. This could vary from basic material elements, such as bricks, to more complete elements, such as a prefab wall. A distinction should be made between the different types of data and type of elements.

Amount

A clear amount of every type of building elements that are being provided by companies or cases and are available for reuse. Also, information about material flows and predicted incoming materials.

Locations / distance to construction site

Due to privacy regulations, sharing information on locations within datasets is difficult. For this research, it is not necessary to be of knowledge which company is in the possession of the material or to which company it is transferred to. Preferably, the end location of the material after transportation is shared. Just the city or the village is adequate, which eventually provides a distance in kilometres.

Reusability potential of material

The reusability of scale is a valuation method that is used for deciding for each building element whether or not the element is fit to be reused. This method is provided by the analysis of the materials and mostly the qualities of the chosen elements should be observed visually to determine whether or not it fits the reusable scale. It depends also on the type of interface and connection with surrounding materials if the material is fit for reuse. These different type of factors are important to determine the costs for reused building materials and the influence of the quality of building elements in relation to the costs for virgin building materials, which is elaborated in section 3.5.2. The levels of reusability are determined by graduation company Alba Concepts and are visible in an example project in Appendix 11.4.

Dimensions

The dimension of the materials available for reuse. If the dimensions of a material are possible to analyse, it could be of big assistance to discover whether or not the use of these elements is realistic. In the type of materials the thickness of structural elements is given, so dimensions length and width could be extra information that could improve the realistic output of the eventually developed model. However, dimensions also create a less wide solution space, if taken into account that every single building element is limited because of its given dimensions, which would make it more difficult to supply hypothetical advice.

Description

Not every building element is the same. Each set of materials should have an extra column to mention comments or a broad description, in order to add any additional information to create more insight into the datasets and improve the input for the model.

Building elements (vertical)

The vertical column of the datasets consists of the different building elements that are being located at the case studies. These columns are divided into building levels from the bottom up. So starting at the foundation, following by floors, walls, roof and other types of building elements that are located within the dwellings or other projects related to the context.

3.3.2 PROJECT-BASED CASES

The first of the three levels of scale is the smallest, the project-based cases. As described in section 2.3.1, the model is based on a small set of projects, which are relatively close by. There are just a few stakeholders involved and in this case, there is one location where the new project should be built, which would provide the different distances for the various locations. To operate a model on a project-based level, a few cases with detailed information of all the different materials available within those cases are necessary. As an example of different cases that could provide the correct datasets, Alba Concepts provided four different projects that are described in the next four sections, divided over the Netherlands (Figure 3.17). An example of a dataset developed by Alba Concepts and used as hypothetical real-life case input is shown in Appendix 11.4.

Figure 3.17 Overview of project-based cases in the Netherlands (own ill.)

3.3.2.1 BO-EX APARTMENTS UTRECHT

Bo-Ex is a housing association located in Utrecht, which offers living space to around 9.000 households (Bo-Ex, n.d.). They have the ambition to participate in a more sustainable world and are influenced by topics such as energy, sustainability and circular economy. In collaboration with Alba Concepts, Bo-Ex designed a circularity strategy, existing of different themes, critical key performance indicators (KPI's) and multiple verification tools. Also, a number of 14 apartment blocks that are outdated are inventoried on the different type of materials, put together in a database. This created a clear insight for Bo-Ex on which materials could potentially be reused or recycled, which makes it a small but extensive dataset.

Figure 3.18 Bo-Ex (Bo-Ex, n.d.)

3.3.2.2 PROJECT DOEN! STATIONAREA ARNHEM

The second project-based case provided by Alba Concepts is 'Project Doen!', which includes the station area of the city of Arnhem. In collaboration with the government, Alba Concepts was involved in a project to refurbish the entire western part of the station area, which consists of 10.000 m^2 BVO. Alba Concepts has been asked by the government to join and advise in the quest to reach the ambitions, related to sustainability and the energy transition. The government separates the ambition circularity into two focus point for the case (Boer, 2018):

Figure 3.19 Rijksoverheid (Boer, 2018)

Circular materials (usage of materials):

- New or reused materials at the beginning of their life cycle (in percentages);
- Reusability of material at the end of the life cycle of the building;
- The technical life cycle of materials (in years).

Circular adaption, detachability (losmaakbaarheid):

- Technical detachability, based on accessibility of connection;
- Physical detachability, based on the type of connection.

To research the different types of circular ambitions, the buildings that were about to be renovated had to be analysed, thus creating a database of the materials present in the buildings, with the given potential of reusability. This database eventually consisted of multiple different types of materials compared to dwelling projects, but still most of the information available could be of use for the model in a different scale or if there is a different demand, for example office buildings or renovation projects. For dwelling projects, the given dataset is not sufficient enough, because it's lack of structural elements and big diversity of different materials.

The example database of 'Project DOEN!' is located in Appendix 11.4.

3.3.2.3 STADSWINKEL TILBURG

The third project-based case is executed by a collaboration of the municipality of Tilburg, Alba Concepts and 'W/E Adviseurs', a sustainable consultant in circularity, project management and project development (W/E Adviseurs, n.d.). The project contained a circular inventory of the building the 'Stadswinkel' of Tilburg, part of the municipality. This resulted in an intensive dataset, divided into multiple sheets, consisting of a BVO of over 21.000 m². The municipality of Tilburg showed their ambition in circularity by pointing out of three main objectives:

Figure 3.20 W/E Adviseurs (W/E Adviseurs, n.d.)

- Reusability of materials within the 'Stadswinkel' itself. The research should indicate advice regarding a select group of building materials and elements that show potential to be directly reused in renovation projects.
- The second possibility for reusability of building elements is within the portfolio of the municipality of Tilburg. For example setting up of materials bank that could provide different projects in the surrounding area of materials, based on similar examples in surrounding municipalities.
- The third option could be in a setup of a possible market place for building materials, such as New Horizon or Cirdax, but this idea is being parked for possible follow up research and action points.

Eventually, the goal for this particular project is to design a material passport of the different materials within the building that have the potential to be reused in future renovation or construction project. If this happens, it would create an innovative database with constantly updated information on the possibilities of reusability of the different materials. However, the current datasets, even though they are very extensive, are also limited to a small stock of building elements, which makes them not relevant for new dwelling projects.

3.3.2.4 DE ALLIANTIE

The fourth project is the only of the set of the project-based datasets that hasn't been executed yet. The case has the potential to create a large set of realistic databases that would be perfect to execute and use as input for the model. The main objective of de Alliantie, which is a housing corporation in the Netherlands with a portfolio of over 50.000 dwellings, divided over multiple cities in the Netherlands (de Alliantie, n.d.), is to analyze their complete portfolio. Together with Alba Concepts, the entire portfolio is divided into 12 different archetypes, based on building age, construction method, isolation values and installations. These 12 different types could easily form an extensive database with many building elements. Unfortunately, due to financial restraints at de Alliantie, de inventory phase didn't take off during the graduation research, but the concept of using an inventory of a portfolio of a housing association offers a lot of potential for the model and further analysis of future projects.

Figure 3.21 de Alliantie (de Alliantie, n.d.)

3.3.3 REGION-BASED CASES

While the former section described the context for the model on a project-level, this section takes a look at the possibilities when using region-based cases. Regions create more possibilities for input and output, because of the larger scale of the context. Often municipalities are involved, to regulate the flow of materials and connect different stakeholders and clients as the project manager of the case. The municipality could act as the middle man, connecting demolition and deconstruction companies to research the locations and inventories the materials, therefore connecting them directly to local housing corporations with the ambition to initiate in sustainable and circular dwelling projects.

3.3.3.1 EME-PLATFORM

The goal of this graduation research is to improve the transition to a CE, by reducing virgin building materials. A single project in a small area does not fulfil the demands for the transition. A context that focusses on a regional level would make a bigger impact in the transition. If more materials could be used as input for a certain model and if the stretch of a certain area for new buildings is bigger, a larger amount of materials are reused and lesser virgin materials are used. However, it is not possible to match all the materials directly with new projects, so it is necessary to find a project or scope from a certain case where it is clear what boundaries are at stake, what kind of materials are used as input and what the demand is for new projects in a certain area. A platform of a kind could be the solution of organizing the connection. An example case is the Excess Materials Exchange Platform (EME), the digital facilitated marketplace that is highlighted in section 2.4.4 by Damen and van Maaren (2018). The scope of the EME platform is the entire Amsterdam Metropolitan Area (AMA) and its surroundings (Figure 3.22). The construction sector within the AMA is used as a scope. Within the building sector, there is a large list of materials which are available to reuse, which are visible in Appendix 11.3. By urban mining these materials, a large database could be created that eventually could be used for new construction projects. The problem is the missing of the connection between the data and the constructors. Also, there is no direct connection between the demand for new construction projects and the supply of the building waste. This connection could be made with the execution of the materials in this region by the digital marketplace of the EME platform.

The EME-platform consists of a collaboration between Alba Concepts, Copper8 and EME. In a hypothetical situation where the tool developed in this research is being connected within the EME-platform, the following subjects show the possible topics to further develop the platform, which connects to the matchmaking module of the platform in specific, also visible in Figure 3.23:

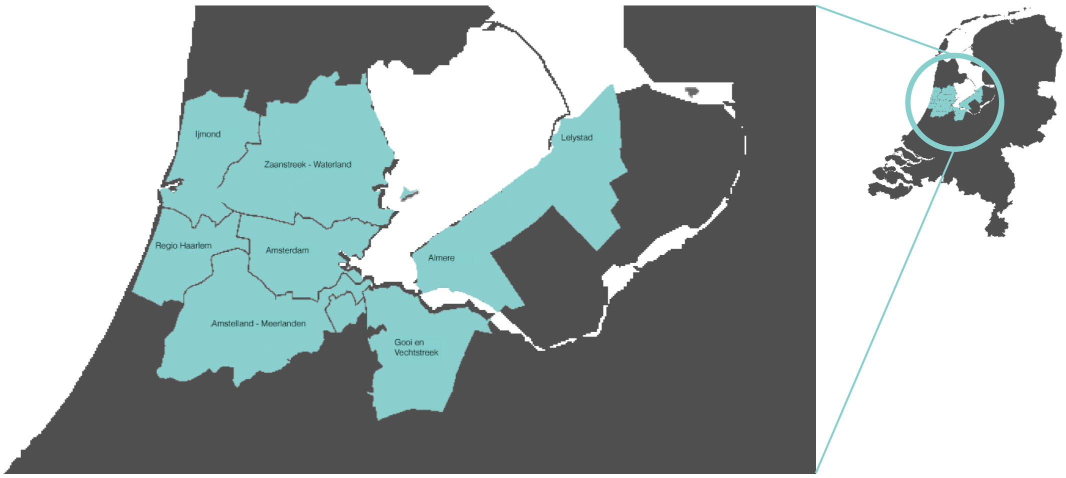


Figure 3.22 Enterprise-based region: Amsterdam Metropolitan Area (own ill.)

1. Gathering datasets of building materials, providing input for the decision-making tool.
2. Exploring the possibilities of different building materials.
3. Exploring the demand side of the research through panel groups with stakeholders.
4. Testing the matchmaking module by the use of case studies.
5. Researching the possibilities within the technical and organisational scope of the platform.
6. Testing the feasibility of the matchmaking module.
7. Designing a tool within digital innovation.
8. Constant updating and improving the decision-making tool.

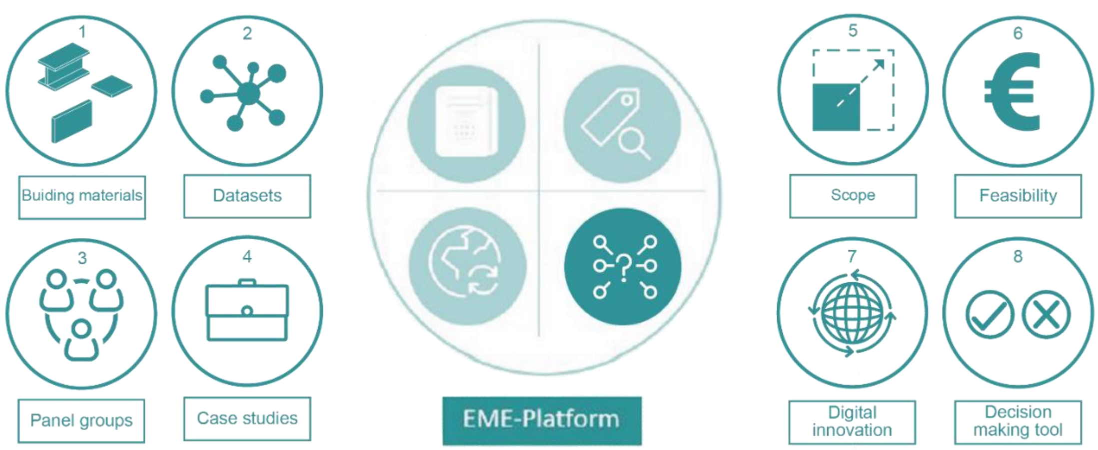


Figure 3.23 EME-platform possibilities in innovation, based on Damen and van Maaren (2018)

These 8 topics are not definitive, but provide subjects that could be researched during a potential collaboration with the organisation of the EME-platform in the future. The results of the tool could be used within the platform as an advisory tool for partners connected to the EME-platform and located within the AMA. Unfortunately, the collaboration between Alba Concepts and EME did not pursue the development of the operational model based on this research, due to lack of reaching a working agreement and collaboration structure. The reasons behind the failed collaboration are explained in the discussion, section 5.1.

3.3.4 ENTERPRISE-BASED CASES

The third level of scale is one of the largest. The enterprise-based cases, as described in section 2.3.3, focus on a system or a typical material flow in a certain region, instead of one or a few small projects within an area. The scope size of this type of system is much larger, which means stakeholders that are in the possession of nation or even European wide datasets are necessary to create a working model. In the next two sections, these types are highlighted.

3.3.4.1 CINDERELA

One of the most interesting projects that comes to mind is the project called Cinderela, a collaboration project between 13 partners from 7 countries in Europe. Their goal is to design a new CE business model for more sustainable urban construction. The partners are a combination of Universities and private companies. The project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 776751(ZAG, 2016).

Figure 3.24 Cinderela (ZAG, 2016)

The Cinderela H2020 tool consists of a database of all the materials that are transported from a first to a second company, due to construction, demolition or other activities. The companies that processed the waste had to record all the transition between their selves and partner, by law. The European Union gathered all the information and created an impressive dataset. Every transition of material is registered and described with code of 6 numbers, which present the type of material, the condition and an extra section with additional information about the quality of the material. Figure 3.25 shows an overview of a visual representation of a flow of materials in a specific area, based on all the different transitions in one year, in this case the year 2016.

Figure 3.25 Cinderela H2020 Complete CDW flow originating from the AMA in 2016 (B. Geldermans et al., 2019)

The sets consist of every type of material that is involved in construction activities. The specifications of the materials differ in extensiveness depending on information such as dimensions, quality and validity. These datasets, due to the completeness and accurateness of the Geodesign Decision Support Environment (GDSE) system, provides a tool which could locate and filter the necessary materials, which are available within the datasets. This tool is developed under the H2020 project REPAiR (REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism) (Pranjić & Mladenović, 2018).

The Cinderela organisation focused on the following three pilots, whilst creating the datasets and organizing experts' conferences such as described in section 3.3:

- Extraction of valuable materials
- Production of secondary raw materials (SRM) based on construction products
- Large scale demonstrations of construction with SRM based construction products

The information about the materials is confidential, which means the use of the datasets should be protected under an NDA agreement, to protect the graduation research and the information about the materials.

3.3.4.2 CIRDAX / CIRKELSTAD / NEW HORIZON

The following companies show small potential to be a possible partner in future collaboration for enterprise-related projects, but did not participate or did not provide enough information to be relevant for the research.

- **Cirdax:** Material management system (elaborated in section 2.4.3). Did not provide access to the system.
- **Cirkelstad**: Mostly focusses on developing cards with possibilities of materials, not an assessment of buildings particularly.
- **New Horizon:** Demolition and investing company, consists of datasets, which could be possible for use as input in the model, but the datasets lack detailed information.

Figure 3.28 Cirdax (Re Use Materials, 2019)

Figure 3.28 Cirkelstad (Büch et al., n.d.)

Figure 3.28 New Horizon (Verkuijlen, 2015)

3.3.5 CONCLUSION

The different cases that are researched as input to test hypothetical operational models turned out to be a bit of a struggle. Most of the potential partners lacked corporation, due to privacy regulations. It resulted in a much smaller amount of datasets that were possible to use for the operational model than expected. The consequences were that this research changed the focus towards a realistic output instead of the input. The operational model should be developed in a sense that it is ready to operate, which means that if there are datasets becoming available to use, for example access to the Cinderela project, the model should be designed in a way that data could be directly implemented.

3.4 DEMAND

Based on the research design presented in Figure 3.2, one of the two paths in the figure is the demand side. With the literature study conducted on material definitions and management systems, the focus within this section is based on the demand for new dwellings and reusable materials within the current dwellings. It has been known for a while that circular materials in dwellings are necessary for the future. As mentioned by the Rijksinstituut voor Volksgezondheid en Milieu (2016), the challenge is to design buildings in such way that all of the materials in them are suitable for high-quality reuse. However, the long life of building structures – 50 to 100 years – makes it difficult to determine how the materials will be dealt with in several decades of time. So it makes sense to analyse the current standard dwellings and determine which materials have the potential to be reused. Also, as mentioned by one of the founding partners of Alba Concepts Jim Teunizen, circular construction projects with reusable materials integrated into new dwellings will be normal, way sooner than expected (Gemeente Amsterdam et al., 2017). This means innovation in circular dwellings is necessary within a short time frame.

"Circulaire bouw gaat, veel sneller dan wij denken, de standaard zijn."

Jim Teunizen, Alba Concepts

So different, both private and public, parties agree on the fact that reusability of materials in dwellings should be standardized and has the future in the construction industry. However, whether or not this transition is feasible for municipalities or housing corporations is an important question, to make this transition of the usage of materials happen. This is where the operational model enters. As explained in section 3.2, the model needs input and generates an output. In the following section, a part of the input is elaborated and how this particular part is related to the final result of the operational model.

3.4.1 DWELLING PROTOTYPES REFERENCES RVO

There are many different dwellings in the Netherlands, which makes it impossible to choose a certain standard dwelling to analyse. Also, a lot of new dwellings are necessary to be built in the future in the Netherlands (ANP, 2019) and it is not even certain if it is possible to complete the demand for dwellings in time. This raises a bunch of questions. What type of dwellings will be built in the future, which materials will be used and why will certain materials be left out of future construction projects? Not all of these questions could be answered yet, so it is important to scale down the analyses of existing dwellings and building materials to a level that is manageable and where already information is available. Fortunately, the RVO (Rijksdienst voor Ondernemend Nederland) provided, in collaboration with Royal HaskoningDHV, six different types of standardized dwellings that nationwide can be used as reference dwellings:

- Apartment block (Krijnen, 2015a)
- Gallery dwelling (Krijnen, 2015b)
- Corner dwelling (Krijnen, 2015c)
- **Standard row-house (Krijnen, 2015d)**
- **Semi-detached dwelling (Krijnen, 2015e)**
- **Detached dwelling (Krijnen, 2015f)**

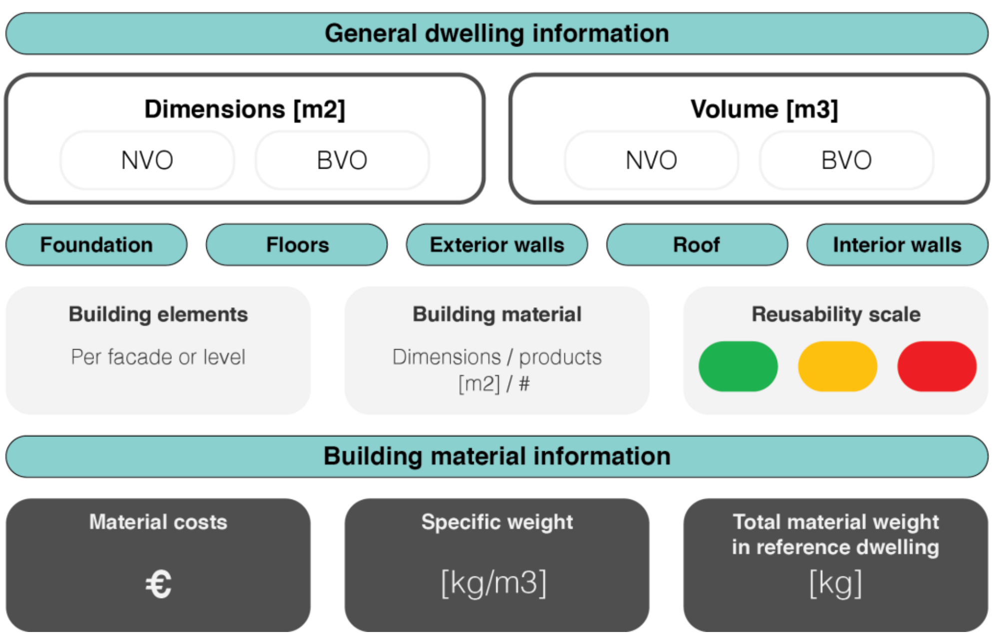


Figure 3.29 Schematic dwelling analysis overview of Excel model (own ill.)

These documents contain all the practical information about the dwellings. Within these six types of standardized dwellings, three have been chosen to be analysed, which are the standard row-house, the semi-detached dwelling and the completely detached dwelling. This choice is based on the fact that the apartment block focusses on multiple dwellings instead of one, which makes it more difficult to determine the number of materials and costs for a single dwelling. This goes as well for the gallery dwelling, which is similar to the apartment block, information on the complete building is lacking. The corner dwelling is almost similar to a combination of the standard row-house and the semi-detached dwelling, so it will not provide any additional information. This leaves the three dwellings to be analysed in the next three sections. The dwellings are analysed on a set of topics related to the materials used within the building, which are of use to determine the right quantities of materials which have the possibility to be reused within the dwellings. This schematic overview of topics is visible in Figure 3.29.

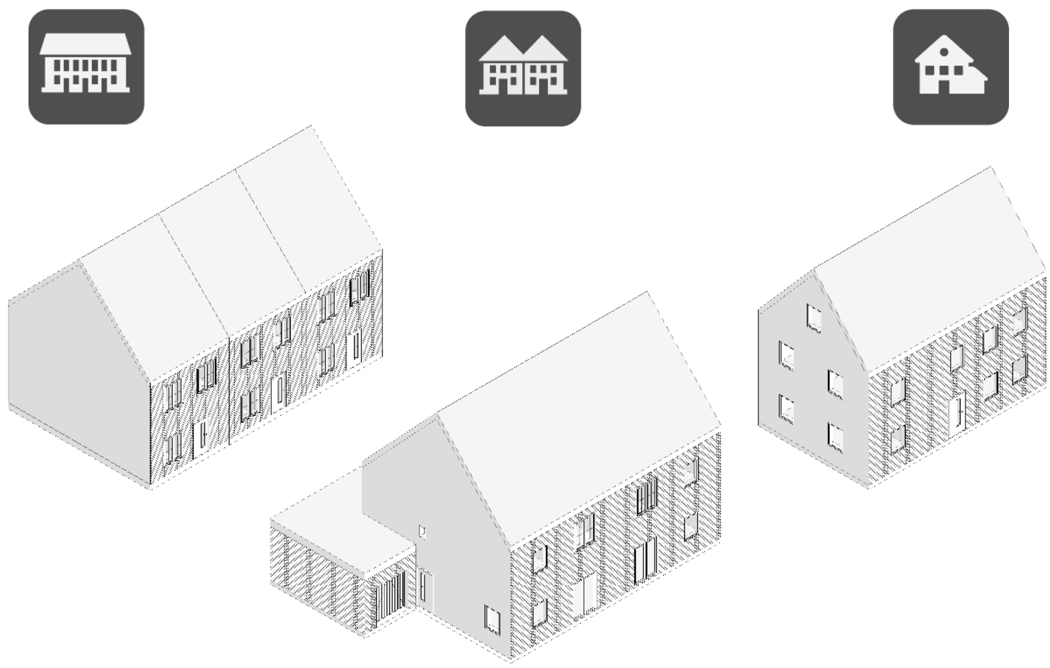


Figure 3.30 Standard-house dwelling, semi-detached house, detached house (Krijnen, 2015d, 2015e, 2015f)

The three different types of dwellings are visible in Figure 3.30. As noticeable, they are similar in materials and height but differ in materials used in the façades, square meters (NVO and BVO) and volume. The overview of specifications and other information regarding the three dwellings are visible in Appendix 11.5, 11.6 and 11.7. These three types of dwellings are used to perform within the project-level model, to create a well-substantiated tool that has the possibility to be up scaled. If so, a significantly larger amount of dwelling types are necessary to use as output for a model, to create diversity and different solutions. The RVO provided another document, which consists of an overview of existing standardized dwellings, based on energy performance and construction year. Over 30 different dwellings are presented, with detailed information on every aspect related to the dwelling (W/E Adviseurs, 2011). If the scale of the project would expand, these types of documents become necessary to define the correct output for the operational model.

3.4.2 REUSABLE BUILDING MATERIALS

Dwellings contain multiple building materials and elements, but not every element is fit for reuse. There are certain factors that determine whether or not materials could have a second life cycle. This is different for every element inside a dwelling. It depends on the different type of materials the element consists of, but also on the interface between the different materials and what kind of connection between the two different materials has been used to connect the interface. This directly reacts to the detachability of building materials, which influences the quality of the material when it is detached or wrecked. The factors that decide how much materials are being influenced by accessibility of connection, detachability of connection and other specifications for materials is visible in Appendix 11.8, which is an overview designed by Durmisevic (2006). When looking at a certain standard dwelling, which has been done in section 3.4.1 and the related Appendices, combining the list of materials to the Shearing Layers concept shown in Figure 3.31 of Brand (1994), the layers 'structure' and 'skin' are, as mentioned earlier within this research, the main layers to focus on for the reusability of the materials.

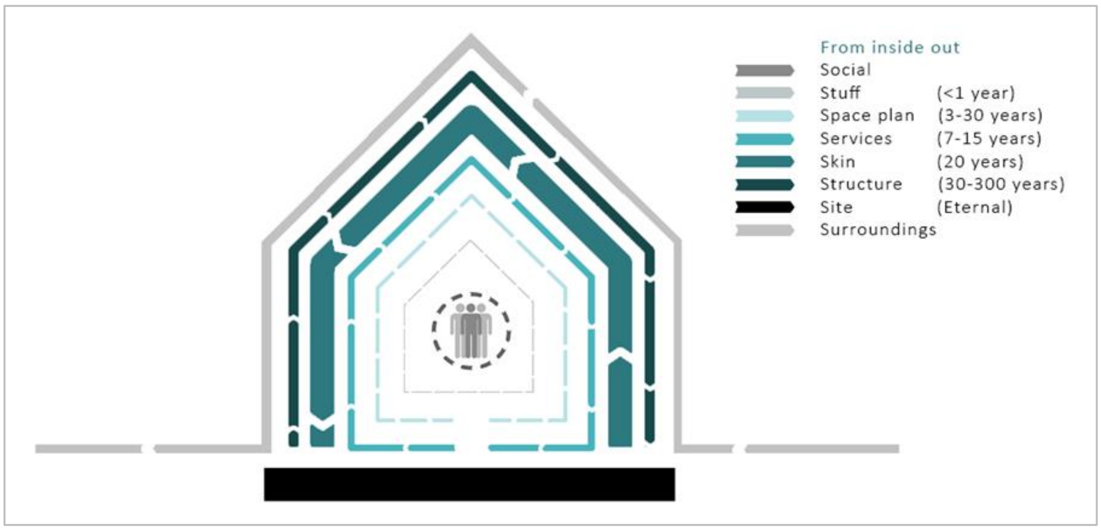


Figure 3.31 Shearing Layers (Brand, 1994)

Looking back at the section where the three reference dwellings have been analysed, a set of six different types of materials show the highest possibility of reusability. The choice on these six types of materials is based on an analysis of the present building materials in dwellings in collaboration with colleague Sven Bögels of Alba Concepts, who is an expert on construction costs calculations and the entire work area of feasibility studies and construction management on dwelling- and utility projects (Bögels, 2019). Figure 3.32 shows six different elements. The type of materials that are used for the elements within the dwellings are based on existing details, which are based on the 'SBR-Referentiedetails' for dwellings (Nieman, 2015). These details consist of exact information on what type of material is used for every particular part of every element, which directly connects to the following six different materials:

- **Floors:** Channel plate floor on the ground level (150mm thickness) and the first or second level (200mm thickness);
- **Exterior wall:** Prefab concrete walls (Residential partitioning wall) and Clickbricks (Façade);

- **Interior wall:** Prefab panels (Ytong or Faay panels);
- **Roof:** Ceramic roof tiles;
- **Doors:** Corridor doors, Façade doors (front) and French door (garden);
- **Windows:** Meranti frame.

The prices and costs of these virgin or reused materials are compared in section 3.5 and are visible in Appendix 11.9.

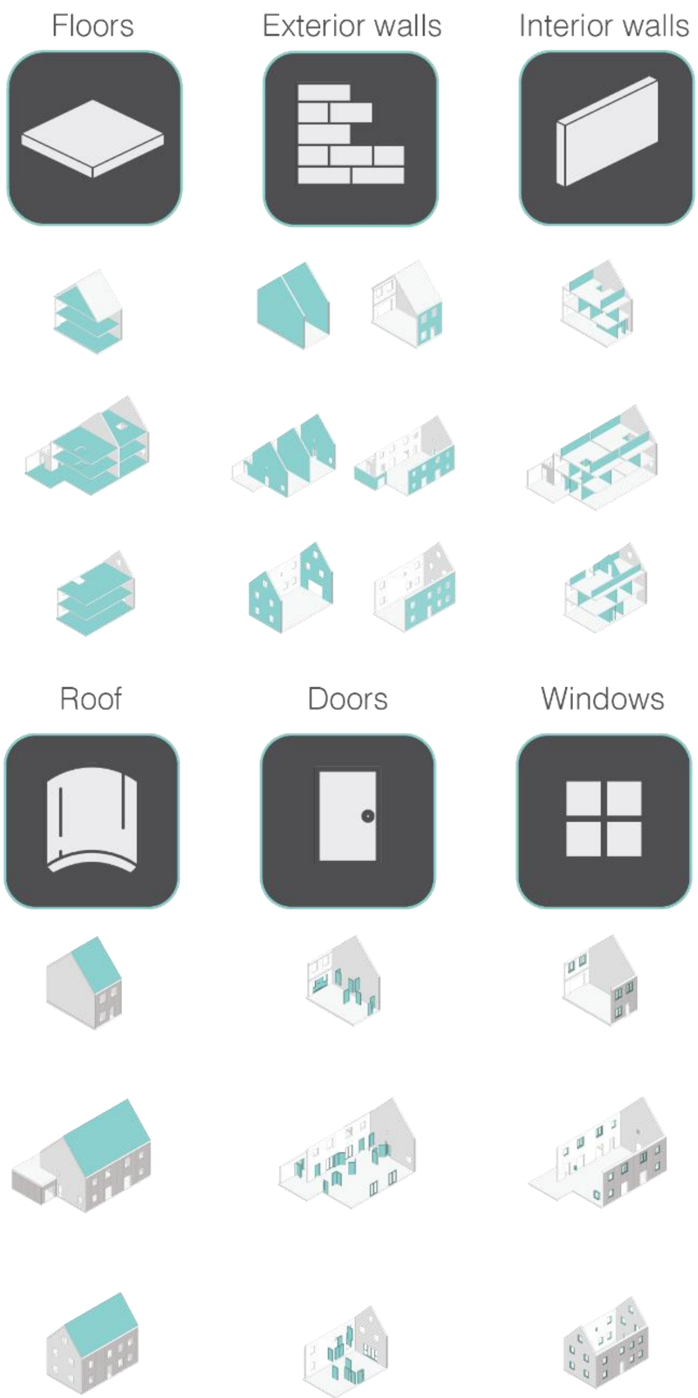


Figure 3.32 Six different building elements with high potential for reusability (own ill.)

3.4.3 PARTICIPATING STAKEHOLDERS

Different questions come to mind when discussing the possibilities of reusing materials for new dwelling project. What is the current housing, renovation or other projects demand in the construction industry? Which parties are willing to collaborate and have the vision to reuse materials instead of virgin materials? What is the current housing demand of the bigger regions in the Netherlands, such as the AMA? The tool which is created has to react on important variables, such as the influence of the stakeholders involved.

To combine the wishes of multiple stakeholders involved related to big housing projects, deleting the middle man and improving the process of reusing materials, as part of the matchmaking tool, it is important to analyse which stakeholders could be involved and in which phase of the process. Also, what the eventual goal of the tool could be for the different stakeholders. For example, it could provide advice for a municipality, to show the possibilities of reusing materials within their region and promote the possibilities to housing associations. Costs and locations factors implemented could provide the setup for an entire structure of housing projects, almost completely designed with reusable building elements and materials. In this case, the municipality would act as project manager, connecting the different housing associations that have sustainable goals to each other and creating projects in which big housing companies could collaborate. The tool would be used in the initiative phase, which creates first insights into the possibilities for new dwellings and helps the municipality in convincing housing associations to cooperate.

The different level of scale also has an influence on the participation of different stakeholders. On a project-level, the only stakeholder involved could be the owner of the dwellings to be demolished, which has the objective to create new dwellings close by. However, when the scale of the project gets larger, multiple locations will provide input in materials. These different locations are frequently in the possession of several companies, so they will have a say within the transition of ownership of materials. Also, multiple deconstruction companies will have to be involved to provide the materials and multiple companies are involved in transportation or storage of these materials. Next, when construction is starting, the tool calculates the possible dwellings to build, but on a larger scale there are multiple locations instead of one. So multiple housing associations or municipalities are involved to create enough construction sites on different locations, which generates even more stakeholders, such as local communities, different construction companies and other housing corporations. If the size of the scope grows from a project-based to a region-based level, the growth of the number of stakeholders should be taken into consideration as well, especially focusing on adjoining costs on ownership, man-hours and legal contractual agreements. The government can also play a role whether or not the tool will provide feasible advice. Due to legal regulations, it could withhold the business case of reaching its full potential. The government could prevent deals between stakeholders to be made because of ownership of ground and land-use plans. The model, when designed on a region- or enterprise-based level, should have incorporated these regulations to see how the outcome reacts to these influences and whether or not the business cases are still feasible.

3.5 FEASIBILITY

The following section elaborates on the feasibility of the study and the operational model. As mentioned multiple times within this research, the goal is to reduce the usage of virgin materials in new dwelling projects. A method to reach that goal is to gain confidence by private stakeholders to invest in reusable material projects. The companies that are interested in reusing building elements should have a clear view on the cost overview of virgin and reusable materials. How the numbers are being decided is elaborated within the following sections. First, the virgin building material costs are determined, based on practice and prices used by contractors in current traditional projects. Next, based on input generated from the current innovation on circular economy of the construction industry, a substantiated calculation on the costs of reused building materials is presented. This chapter also shows the sources of the calculation that are used as input. These sources consist of hypothetically existing dwellings, with a set of building materials at the location and a certain distance connecting the old and new location.

Costs in the construction industry is an extensive topic. The multiple traditional building phases of dwelling projects, starting from initiative to design, followed by construction and finally the maintenance of the project, have a lot of expenses related to the project. Also, the number of stakeholders in large projects, as mentioned in section 3.4.3, brings along many factors to take into account. So for this research, it is necessary to define a scope on which the calculations are limited. Figure 3.33 shows the different costs that are components of a building project (Gemeente Amsterdam et al., 2017).

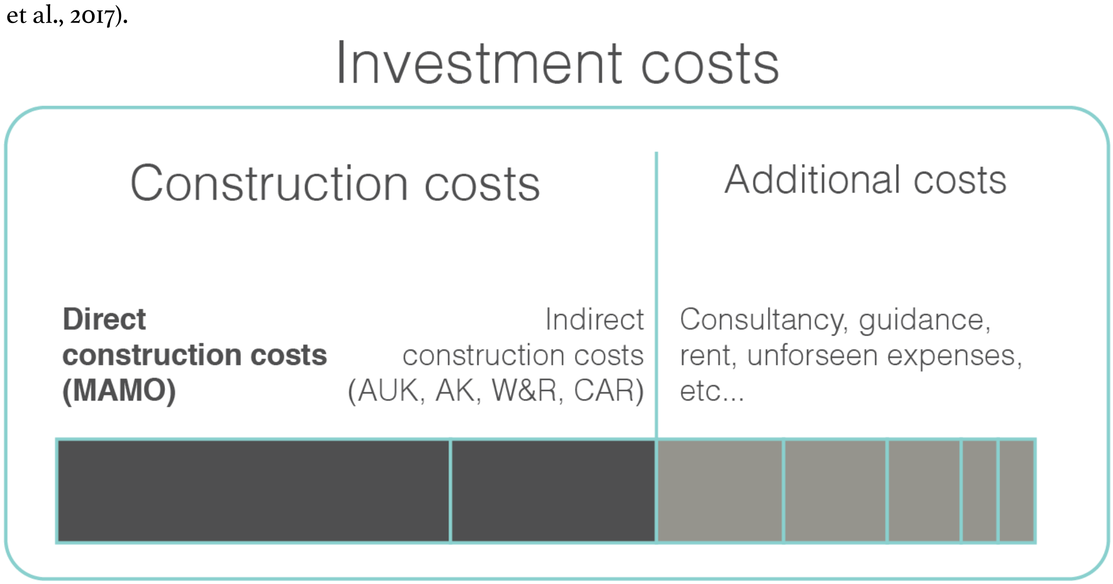


Figure 3.33 Investment costs of a construction project (Gemeente Amsterdam et al., 2017)

Direct construction costs (MAMO: Materiaal, Arbeid, Materieel en Onder aanneming) (Figure 3.34)
Indirect construction costs (AUK; Algemene uitvoeringskosten, AK; Algemene kosten, W&R; Winst & Risico, CAR en prijsstijgingen)

This is just a small conceptual overview of the most general costs. For this research, the direct construction costs are taken into account into the calculation of the costs for virgin and reused materials. Due to the fact that indirect costs probably are similar whether or not the building is constructed with either virgin or reused materials on a project-based scope, the indirect and additional costs are not taken into account. Also, labour costs such as man-hours will probably be similar for the different materials as well, so these are not adopted into the formula as well. The projects which are initiated with reusable materials will eventually show what kind of additional and indirect construction costs are at hand. But because the still yet to be executed projects, there is not much information on budget overviews of these types of projects yet. There simply haven't been that much projects completed yet, in which the usage of reusable materials had been taken into account from the beginning to the end. This makes it not possible to use the number of costs from traditional projects and implement them directly into the costs of projects initiated with the goal to only focus on reusable building materials. So for this research, the direct construction costs are only taken into account.

Figure 3.34 Direct construction costs (MAMO) (Gemeente Amsterdam, Concepts, & Copper8, 2017)

This goes the same for the different aspects of the direct construction costs. As shown in Figure 3.34, the construction costs consists of the building materials, the labour performed by workers, the equipment used and the usage for subcontractors. The last three topics will probably have the same kind of price budget compared to traditional construction projects, but due to the fact no projects of worth mentioning scale of context being executed yet, these costs will not be taken into account.

It is recommended to adopt the indirect costs into the model as soon as possible in cases with different size of scale and amount of stakeholders, to make sure the financial output of the model is as realistic as possible and directly adaptable into cases. Multiple stakeholders will bring extra costs into the calculation as well, such as transition of ownership, contractual agreements and other legal-related subjects.

3.5.1 COSTS VIRGIN BUILDING MATERIALS

Figure 3.35 Cobouw (Cobouw, n.d.)

The traditional construction methods use overall virgin building materials for new projects. The costs for traditional building methods are located on online platforms with an overall view of the different types of costs. These overviews are based on real-life projects, but the numbers differ in context, related to the different elements regarding the source. For this research, most of the traditional virgin materials the source of the costs is located at 'Cobouw Bouwkosten' (Cobouw, n.d.). This website shows an overview of almost all the different elements and materials of different sizes and types. If the specific material is not located at Cobouw, other websites are referred to for the costs estimation, mostly contractors or companies that deal in the same materials as well.

Based on the 'SBR-referentiedetails', the correct type of materials could be determined that are located in the dwelling prototypes, as elaborated in section 3.4.1. Afterward, the costs per square meter [€/m²] of each material is cross-referenced with the different suppliers and the correct type of material. The materials listed at Cobouw do differ in specifications regarding the total amount of costs per square meter. For example, the specifications of the costs for prefab concrete exterior walls consist of every small detail in constructing the facade. While in this research, only the direct material costs are taken into account. So the recipe of each material on Cobouw has been checked and labour costs or other additional aspects are left out. Appendix 11.9 shows an overview of all the different types of material for each element and the related costs for every type of material per square meter, visually represented in Figure 3.36. The strokes in the overview in the Appendix that are marked in green have the closest connection to the design of the details, based on the dwelling prototypes, so these are chosen as reference for the calculation of the costs.

In this overview, the lifespan of the chosen elements has been attached as well. It is important to realize the degradation of the quality of materials due to aging. The lifespans of the materials are based on the website 'NIBE, Experts in sustainability' (NIBE, 2011), which has detailed information of almost every structural building product in every layer of buildings. Next to lifespans, NIBE has information on subjects as environmental class, general transport distance, weight per functional unit. The reason why lifespans are attached within the information overview of the virgin costs is related to the calculation of the material validation of the reused materials, which are elaborated in section 3.5.2.3.

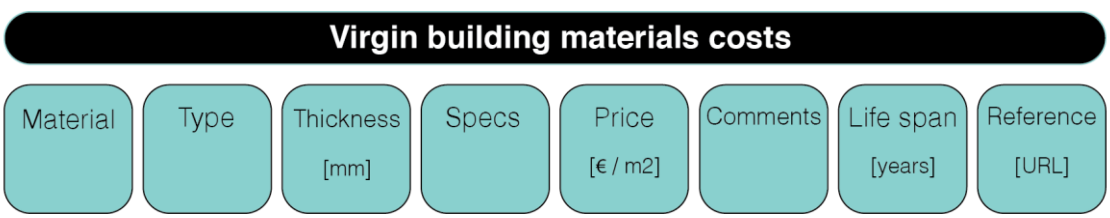


Figure 3.36 Virgin building materials costs schematic overview of Excel table located in Appendix 11.9 (own ill.)

3.5.2 COSTS REUSABLE BUILDING MATERIALS

The second section of the feasibility study of this research concerns a topic that is still yet to be developed, also in practice. The calculation on how to determine costs for reusable structural building elements is a discussion that is still going strong. Multiple companies and research organisations are cracking their heads on the different factors that should be taken into account when calculating the costs. A few of these factors are discussed and presented within the following section. The difficulty of calculating costs for reusable materials depends also on information coming from practice, but the problem is there are not that many large scale projects executed yet, which involve the reuse of building materials on such a large or complex scale, meaning creating almost an entire dwelling out of structural materials. This means the formulas to determine the costs are based on assumptions, substantiated from literature and reports created by experts in the field. Also, as shown in Figure 3.37, at the 26th of August 2019, a discussion group took place with the colleagues from Alba Concepts, which are experts of consultancy in circularity, sustainability and project management. During the discussion, the different factors that influence the costs of secondary building materials for new dwelling projects are being discussed, from expertise of personal knowledge and reference projects. The comments and insights are being implemented in the following sections as well.

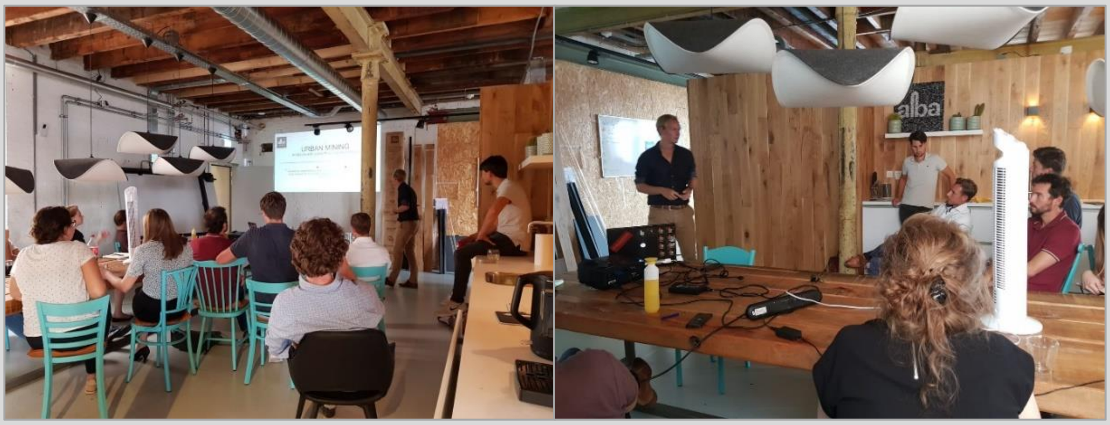
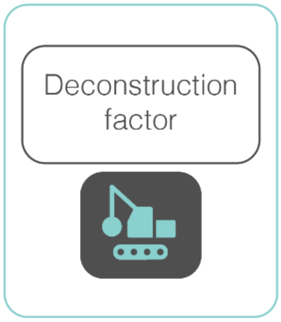


Figure 3.37 Discussion session experts Alba Concepts 26-08-2019 (own image)

3.5.2.1 DECONSTRUCTION

In the process of urban mining building materials from existing dwellings, the first obstacle to overcome is to deconstruct the dwellings to obtain the different materials. Deconstruction costs are tricky to determine, due to the many different techniques of demolition, the many different materials and the different interface between the materials which makes it more difficult to obtain the value of the material. Also, multiple companies that are active in the field of the demolition of buildings, are not used to the process of deconstructing buildings to save the materials but mostly just demolished the dwellings to a state where it could be only recycled or down cycled.

The market on reusable materials is not at the level yet that every demolition company focusses on maintaining the value of building elements. This means there are not many correct feasibility studies or calculations performed yet on this concept. Though there is an ongoing project, which is a research of a collaboration between Alba Concepts and 'De Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek' (TNO), commissioned by Madaster. This research focusses on calculating and determining the valuation of commodities or recourses (Madaster et al., 2018). The formulas used to determine the deconstruction costs can almost be directly applied within this research, regarding some minor changes or a different interpretation of the factors. Figure 3.38 shows the formulas and the different elements that influence the final financial outcome, which is created within the research of Madaster et al. (2018).



Sloop- en demontagekosten k.1 uit gebouw

$f_{k.1.1} = ((TSDK_{gebouw} / m_{gebouw}) * m_{k1}) * (1 - LI_{k.1}) * i_{funct./techn.ld}$ ⇒ uitkomst in €

Waarbij:

$f_{k.1.1}$	Sloop- en demontagekosten k.1 uit gebouw
$TSDK_{gebouw}$	Totale sloop- en demontagekosten gebouw in één bouwstroom (nominaal)
m_{gebouw}	Totale massa gebouw ($= \sum m_{structure;skin;services;spaceplan}$)
m_{k1}	Totale massa k.1 ($= \sum m_{structure;skin;services;spaceplan}$)
$LI_{k.1}$	Losmaakbaarheidsindex in % (zie circulaire tab, default 1)
$i_{funct./techn.ld}$	BDB-index op einde functionele of technische levensduur product

Totale sloop- en demontagekosten gebouw in één bouwstroom (nominaal)

$TSDK_{gebouw} = m^2 \text{ bvo} * \text{gem. } €/m^2 \text{ bvo} * f_{functie} * f_{hoogte\ gebouw}$ ⇒ uitkomst in €

Waarbij:

$TSDK_{gebouw}$	Totale sloop- en demontagekosten gebouw in één bouwstroom (nominaal)
m^2 bvo	Aantal m_2 bruto vloeroppervlakte gebouw
gem. €/m^2	Gemiddelde sloop- en demontagekosten per m^2 bvo gewogen naar Layers of Brand
$f_{functie}$	Factor voor functie van het gebouw
f_{hoogte}	Factor voor de hoogte van het gebouw

Figure 3.38 Deconstruction costs formula, total deconstruction costs formula (Madaster et al., 2018)

The first formula calculates the entire demolition costs for a building. As a reference, the dwellings presented in section 3.4.1 are used. Depending on each building material, the costs compared to the complete dwellings will differ and calculated back to costs per square meter. The LI (Losmaakbaarheidsindex) stays in this calculation at factor 1, so the table presented in Appendix 11.8 which shows the disassembly factors does not apply to the calculation, due to the fact that the reference projects at hand are traditionally constructed, without considering future disassembly methods. The advice concerning this calculation is to take disassembly factors in new dwellings into account, which makes the future perspective for developers more feasibility attractive because the demolition costs will decrease if the dwellings are designed to be deconstructed and not lose any value on the materials. Thus generating fewer costs for reusable materials. The BDB-index (bouwkostenindex), together with inflation and the discount rate of materials hasn't been taken into account within the calculation. Price indexing only takes place when a time period is involved, which is not in this calculation.

When the total deconstruction costs are determined, the deconstruction costs for a single material can be determined, based on the square meter BVO of the reference dwelling and the average deconstruction costs based on the Layers of Brand (1994). The results of the calculation of the costs are visible in Appendix 11.10 for the six different materials, mentioned in section 3.4.2.

3.5.2.2 TRANSPORTATION

The second calculation is based on the transportation of the materials. Figure 3.39 shows the costs formula for taking materials to a processor, but the concept for the calculation can be adapted for transportation of building materials as well. For the calculation to be executed, a distance from the building spot where existing dwellings are located to the new building location should be determined, creating a certain distance (*A*). These exact distances are shown in section 3.6. Based on the price for transportation units per kilometre, the cost for a single ride of materials can be calculated (de Transporters, n.d.). Eventually the formula calculates a certain amount, which shows the price per square meters [€/m²] or per kilograms [€/kg]. Appendix 11.10 shows the calculation method and the final prices for the six building materials per square meter.

Additionele vervoerskosten naar verwerker

$f_{k.1.2} = A_{verwerker} * €/km * f_{bgv} * i_{cor;funct./techn.ld}$ ⇒ uitkomst in €

Waarbij:

$f_{k.1.2}$	Additionele vervoerskosten naar verwerker
$A_{verwerker}$	Afstand naar verwerker (in km)
€/km	Prijs per kilometer
f_{bgv}	Factor voor beschikbaarheid goedkoop vervoer
$i_{CPI;funct./tec}$	Inflatiecorrectie op einde functionele of technische levensduur product

Figure 3.39 Additional transportation costs formula (Madaster, TNO, & Alba Concepts, 2018)

3.5.2.3 MATERIAL VALIDATION

The materials in dwellings that are reused are probably old, damaged, or affected in some kind. This is where the material validation calculation comes into play to determine the influence these factors have and what it means for the costs to reuse these materials. The validation factor consists of three subjects, which are elaborated in this section and are also visible in Figure 3.40. The concept of the material calculation is established in collaboration with expert colleagues of Alba Concepts (Stijn van Enckevort, Sven Bögels, Jip van Grinsven) and after the discussion group on the topic of material validation costs, elaborated in section 3.5.2.

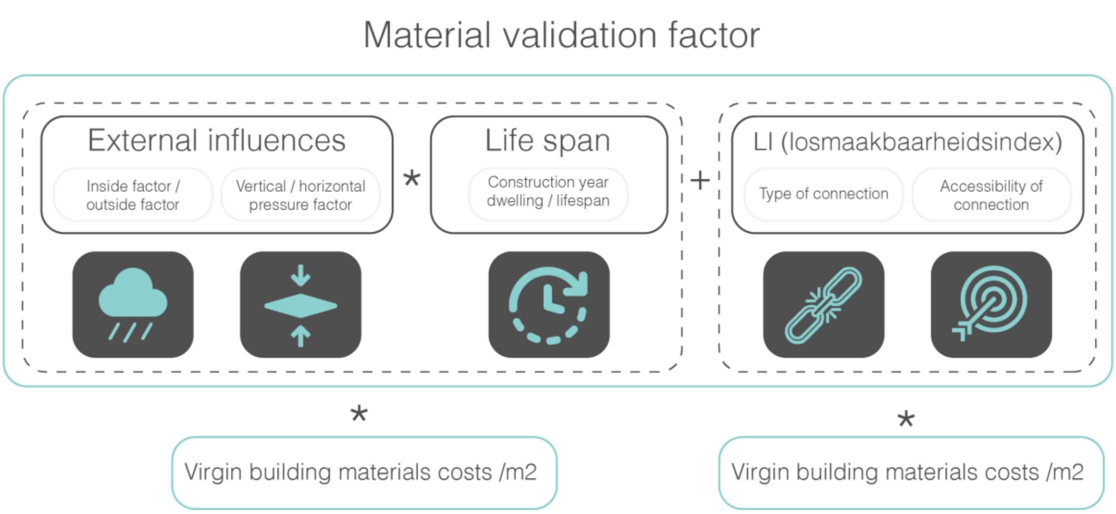


Figure 3.40 Material validation factor reusable building materials (own ill.)

External influences and life span

The building elements that are part of the dwellings are affected by external factors over time. The first factor in this case is whether or not the material is located on the inside or the outside of the façade. Materials located on the outside could be more damaged in relation to materials on the inside due to weather factors or other external influences. The same goes for the inside. The exact factors of how much this influences the different materials is related to the location within the building. Next, most of the building materials could be influenced by pressure of other elements within the building, due to a vertical or horizontal connection or interface between the materials or elements. Both of these external factors are influenced by time, so the age of the building should be considered as well. This is where the life span calculation of each material comes in. Every type of building materials has a different life span, depending on several factors, as already elaborated on in section 3.5.1 (NIBE, 2011). It is also necessary to have information on the construction year of the dwelling. If this is a known fact, the life span of materials could be used as reference to determine how much the material is influenced over time. Figure 3.41 shows a drawing of how the concept of time would influence the value due to the different factors (Van Enckevort, 2019). Starting at a certain value for a material, over time the different factors will influence the material value and so raising the costs for the materials if still to be used for new dwellings. If for example the material is outside, the material is influenced over time more significantly compared to if it should be inside. This creates a quicker drop of value. The same goes for the pressure factor.

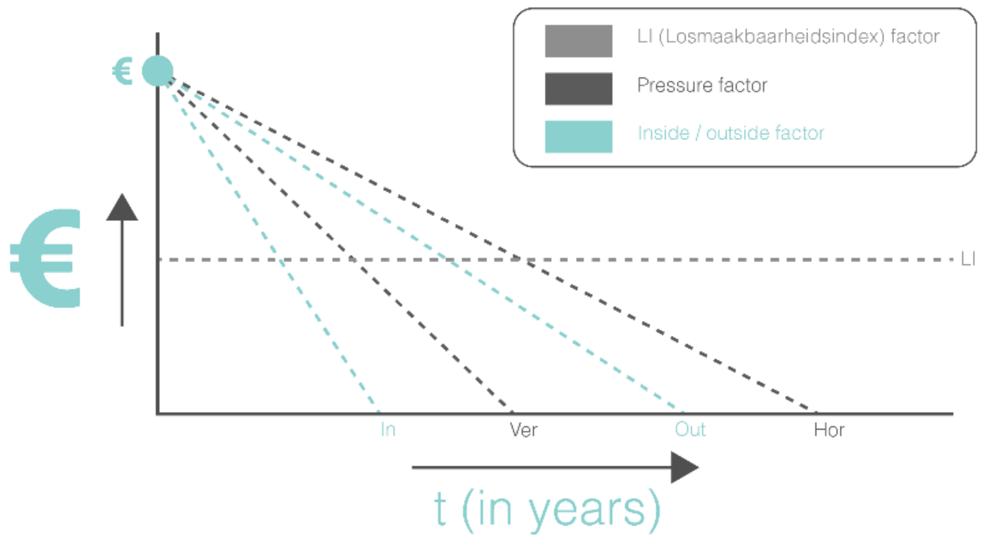


Figure 3.41 Valuation materials over time (Van Enckevort, 2019)

LI (Losmaakbaarheidsindex)

The second factor is based on the Building Circularity Index (BCI), designed by van Vliet (2018). As mentioned in the literature study in section 2.5.2, the BCI consists of two components: the MI (Material index) and the LI (Losmaakbaarheidsindex). The LI is the index that is used for the calculation within this research, due to the two types of factors that are involved. The type of connection of the interface of the material and the accessibility to this connection. Based on the disassembly factors by Durmisevic (2006), the amount of influence of the factors are connected to the LI, which is visible in the two first table blocks of the table in Appendix 11.8. The LI is not taken into account within the life span of the material. Looking at Figure 3.41, at the moment of construction (*t* = 0), the material will drop directly to a certain point on the value scale. This downgrade happens directly because of the fact that once a building is constructed, the type of connection and accessibility of connection is determined and will not change, increase or decrease, over time, not taken any reconstructions or renovations of dwellings into account.

Appendix 11.11 shows an overview of the calculations performed on the six different building elements. This overview also gives insight in the factors used for the calculation, the type of materials, the type of connection, the type of accessibility and the different influences by internal and external factors.

3.5.2.4 CONCLUSION

The different factors combined provide a formula to calculate the costs for the reusable building materials per square meters, which is visually represented in Figure 3.42. It consists of the sum of the deconstruction factor, the transportation factor and the material validation factors. An important notice is that this formula is based on the assumption and interpretation of different factors, which are coming from experts that are active in the field of circular construction industry, but the formulas haven't been applied to cases yet. The overview of the chosen factors are visible in Appendix 11.11. The numbers that are used do not relate to a source yet, because it is difficult to substantiate these factors. Also, the creation of this formula puts different pieces from the world of defining the value of structural reusable materials together. Every single part of the calculation should be tested and substantiated before the formula can be applied in practice. When it is eventually being used, the test cases show which factors have the most influence in the outcome of the costs, also directly putting the reliability of this factor in perspective. So the results coming from these calculations should be analysed critically when developing similar formulas in the near future, for further innovation of the building sector. For now, the formula provides calculations for the operational tool. The execution of the model and the results are presented in the following sections. Section 5.3 looks back on these factors, discussing on the critical factors and which part has the most influence within the final outcome of the calculation.

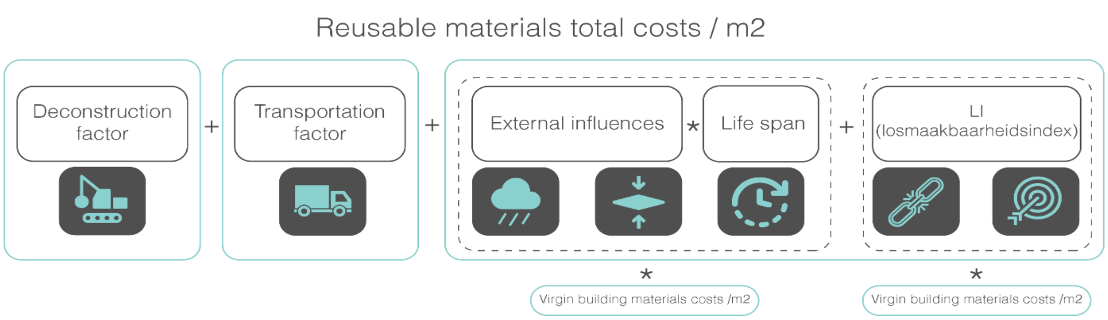


Figure 3.42 Reusable materials total [€/m²] (own ill.)

3.6 EXECUTION

The goal of this research is to reduce virgin building material usage within new dwelling projects. To reach this goal, the tool developed together with the input, coming from literature and real-life cases should be executed. To execute a case, the input should be complete and sufficient enough, based on the different levels of scale. This chapter describes briefly the demand necessary for the different levels of scale to operate and how the data is being used to test the qualities of the model. Eventually, the tool should provide significant results to substantiate the value of this research, which is elaborated in chapter 4 and discussed in chapter 5.

As mentioned in section 2.3, the tools input and eventual output could be divided into three levels of scale. Next sections show how this research interpreted the levels for the execution of the tool and what datasets are used for each level.

3.6.1 PROJECT-BASED MODEL

The smallest level of scale is the project-based model. This level of scale is used as the development level of the correct output numbers, such as the dwelling demand described in section 3.4 and the feasibility in section 3.5. The model's input consists of two hypothetical sources, due to the fact that the real-life project cases presented in section 3.3.2 did not provide significant data to test the qualities of the model. These two sources are located at a certain distance from the hypothetical construction site. The materials available at the location are coming from a series of reference dwellings. The construction year of the reference dwellings is also hypothetical. These hypothetical input factors are necessary to make the model run and create a realistic output. This output consists of a series of dwellings, based on the dwelling prototypes, but also a comparison of costs between if the dwellings would be built with only virgin building materials or if the dwellings would be built by mostly reused building materials. Other factors necessary for the input should be decided by potential clients, such as the budget willing to invest and the number of dwellings to be built of each type, minimum and maximum.

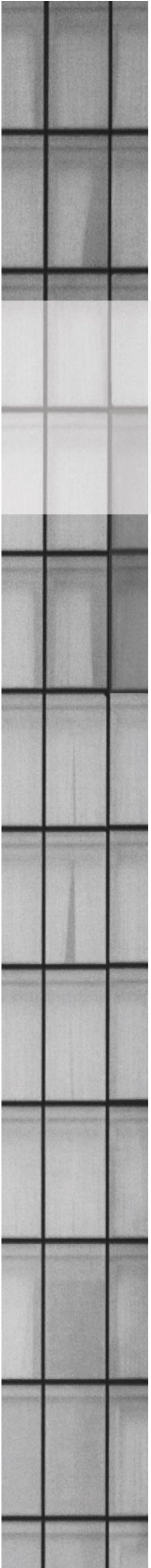
In Appendix 11.11 it shows the input page of the Excel model, with the hypothetical input. This is an example of a potential interface overview that could be used in practice. Section 6.1 elaborates on the recommendations of the interface of the tool for practice.

3.6.2 REGION-BASED MODEL

The second model is based on the AMA-input, presented in section 3.3.3. This region-based model is larger scaled in comparison to the project-based level, because of the bigger input. Instead of a few projects as data input, the region provides materials for the cases on multiple locations, with a larger budget. The development of the region-based model focused on experimenting with the possibilities of the 'What'sBest!' add-in for Microsoft Excel, to research the possibilities in scale, width and amount of variables and constraints. The data for this model is hypothetical as well, due to the fact the collaboration with EME, as earlier mentioned in section 3.3.3.1, did not continue and why no actual datasets were provided by the EME-platform. This level of scale has the potential to be realistic and to provide insight and advice for larger projects by housing corporations or municipalities. The tool just needs real-life cases and datasets implemented to generate actual results. For now, the project-based tool provides the results necessary to substantiate the conclusion of this research, while the region-based tool provides recommendations and further innovation possibilities for the future.

3.6.3 ENTERPRISE-BASED MODEL

The model that is executed on an enterprise-based level is in need of a tool or program that has input on material flows of a scale much larger compared to the other levels of scale. The collaboration with the Cinderela project, elaborated in section 3.3.4.1, promised to be an interesting input. However, the process of collaborating between an intern at a private company and the project organisation funded by the European Union turned out to be a more difficult process than expected. The organisation is willing to collaborate in the near future, meaning sharing access to the databases and in return providing the input of this research as additional material for the Cinderela project, if a clear Non-Disclosure Agreement (NDA) is signed. This document consists of the datasets, without sharing any private information on correct locations of companies or other stakeholders involved. The sharing of this explicit data could be in contrary to the privacy regulations. If the Cinderela project is willing to accept the contractual agreements, the collaboration could take place and the datasets could be implemented in a future enterprise-based model. However, this model will be interesting to develop in further research, thus it is discussed in chapter 5.



PART 4 FINDINGS

In the former chapter, the entire setup of the main deliverable for this research has been presented, elaborated, substantiated and developed to a model that is being prepared to be used in practice. The model generated an outcome, based on different levels of scale, substantiated input and output. This chapter focusses on the main findings within these results, the financial numbers presented in the feasibility section, but also the scenario's to take into account when running this model and how they influence the results and possible future use of the model. Finally, the results, as presented in the research setup in section 3.1, give feedback on the main- and sub research questions in the conclusion of this research. This creates aspects on which the model could be improved, expanded or taken different scenarios into account in which the model could work differently. This is the connection to the recommendations overview in section 5.4. Other main findings are presented in the following sections. The results mostly focus on the main model developed on the project-based scale and partly results are elaborated on the hypothetical, yet still to be developed in future projects or research, region-based and enterprise-based models.

4.1 MAIN FINDINGS

Operational research is used to solve complex projects related to real-life cases. Through the usage of the operational model, a calculation took place that eventually shows the comparison in costs between the usage of reusable building materials and virgin building materials. During the collection of the input and output of the data to use for the operational model, collecting information showed the difficulty of collaborating with external stakeholders. The lessons learned and recommendations for future projects concerning such a large scale of sharing information is discussed in chapter 5. Actual real-life cases with reusable material are exchanged for hypothetical datasets, which generates the final output of the project-based model. These outcomes can be divided into the following subjects, based on section 3.2.4 and Figure 4.1:

- Reused building materials.
- Reference dwellings to be built.
- Financial comparison between reused and virgin building materials.

The complete overview of the output of the project-based model is visible in Appendix 11.13.

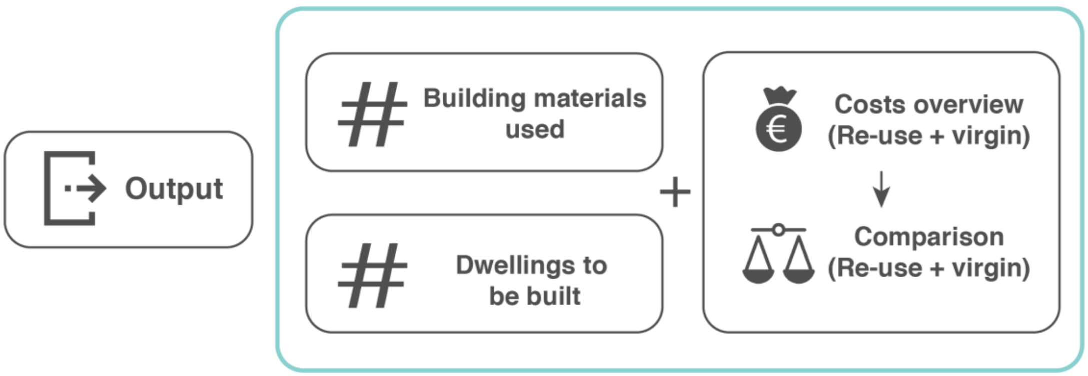


Figure 4.1 Output specifications operational model (own ill.)

4.1.1 MATERIALS

The first output of the operational model is the actual overview of materials used for the built dwellings. How many materials are taken from which source and how many leftovers are there in different locations? For every material, a part of each source is used for the different dwellings to be built. How much has been used from a certain location depends also on the distance of the location. The bigger the distance, the higher the costs are from a certain point out. In the example presented in a project-based model, visible in the input page in Appendix 11.12, the distances are pretty close in range from each other. If the influence of transportation costs would be a bigger factor within the calculation, the division of materials over the eventual construction locations would probably be different. If the distance would be much bigger, the model would give an infeasible solution.

The materials used for this calculation are based on discussions with experts from Alba Concepts. This means that the materials in this overview show potential to be reused. However, to construct a complete dwelling, much more different materials are necessary. For now, only the possible reusable materials are taken into account in the calculation and discussed in section 3.4.2. To finalize the building, virgin materials are necessary as well, such as isolation, installations et cetera. This is further discussed in section 5.4. Table 4.1 shows an overview of how many square meters of each material are used for each dwelling reference type. Also how many materials are used from each source is shown.

Output

Dwelling type configuration				
Dwellings	*Dwelling type*	*A: Row-house*	*B: Semi-detached house*	*C: Detached house*
	Optimal	10	50	52

Amounts of material used per type and dwelling type				
	Dwelling type	*A: Row-house*	*B: Semi-detached house*	*C: Detached house*
Floors	Channel plate floor BG	455	3.588	3.170
	Channel plate floor 1e / 2e	676	3.729	5.574
Exterior wall	Prefab concrete	1.110	7.399	4.043
	Clickbrick	347	4.327	5.432
Interior wall	Panels (Ytong/Faay/other)	528	3.030	4.445
Roof	Roof tiles	645	3.795	4.561
Windows	Glass + frame	245	850	2.143
Doors [#]	Front door	10	50	52
	Corridor door	70	350	464
	French door	0	100	0

Amounts of Reused building material used per type and source			
	Used	*Source O*	*Source P*
Floors	Channel plate floor BG	3.213	4.000
	Channel plate floor 1e / 2e	3.980	6.000
Exterior wall	Prefab concrete	9.500	3.052
	Clickbrick	10.000	106
Interior wall	Panels (Ytong/Faay/other)	8.000	3
Roof	Roof tiles	5.000	4.000
Windows	Glass + frame	3.238	0
Doors [#]	Front door	112	0
	Corridor door	884	0
	French door	100	0

Table 4.1 Output materials project-based model (own table)

4.1.2 DWELLINGS

Table 4.1 also shows how many dwellings of each type could be built with the division of available reusable materials at the two sources. This number is calculated within the solution space and is the most optimal division. This is based on the minimum and maximum demand for each type of dwelling, stated by a hypothetical client. The dwellings are based on the reference prototypes, presented in section 3.4.1. The results show that it is more cost-efficient to build the second and the third prototype, based on the calculations of the costs for the materials, which is discussed in the next section. It also shows the potential of what amount of dwellings are possible, based on the available materials on each source. When multiple reference dwellings are taken into account, or located at different construction sites, the model has to be extended, creating a set of multiple variables that has to be implemented. An important notion is similar to the previous section: The dwellings cannot be built with just the materials at the different sources. Multiple virgin materials should be added to completely construct the dwellings. These are not taken into account in the feasibility overview, due to the fact that the goal of the model is to give insight in material costs for the potentially reusable building materials.

4.1.3 FEASIBILITY

The third main findings section relates to the financial side of the model. As mentioned in the output overview of the operational model, a comparison between the costs of reusable and virgin building materials are calculated. In chapter 5 the discussion among the results is elaborated, based on the choices made within the research and the results stated within this section.

Figure 4.2 Output amount of dwellings (own ill.)

Of the three theoretical levels of scale, the project-based model has been executed within this research. The input of this model has been described in earlier sections. The different materials that are taken into the comparison are calculated, based on formulas and assumptions made in the feasibility section 3.5. For every material, the model calculates the total budget of the type of material for all the reference dwellings to be built. This generates an overall costs price for every type of material, potentially reused from a source compared to the costs if the materials where virgin. The comparison between each of these materials shows a difference in costs, presented as a percentage of how much more or less it would cost to use reusable materials. These numbers are summed up, to finally result in a total overview of the costs for the project.

Table 4.2 shows an overview of the financial comparison of the project-based model. The first overview shows the difference in costs for the dwellings to be built in total with reusable building materials (light blue) compared to dwellings built with virgin building materials (grey). The second overview shows the difference in percentages of the costs for the dwellings and each specific building element. The size of the circle shows the size of the difference, green when it is cheaper to use the reusable building materials and in red shown when virgin materials are cheaper. Appendix 11.13 shows the entire output of the operational model.

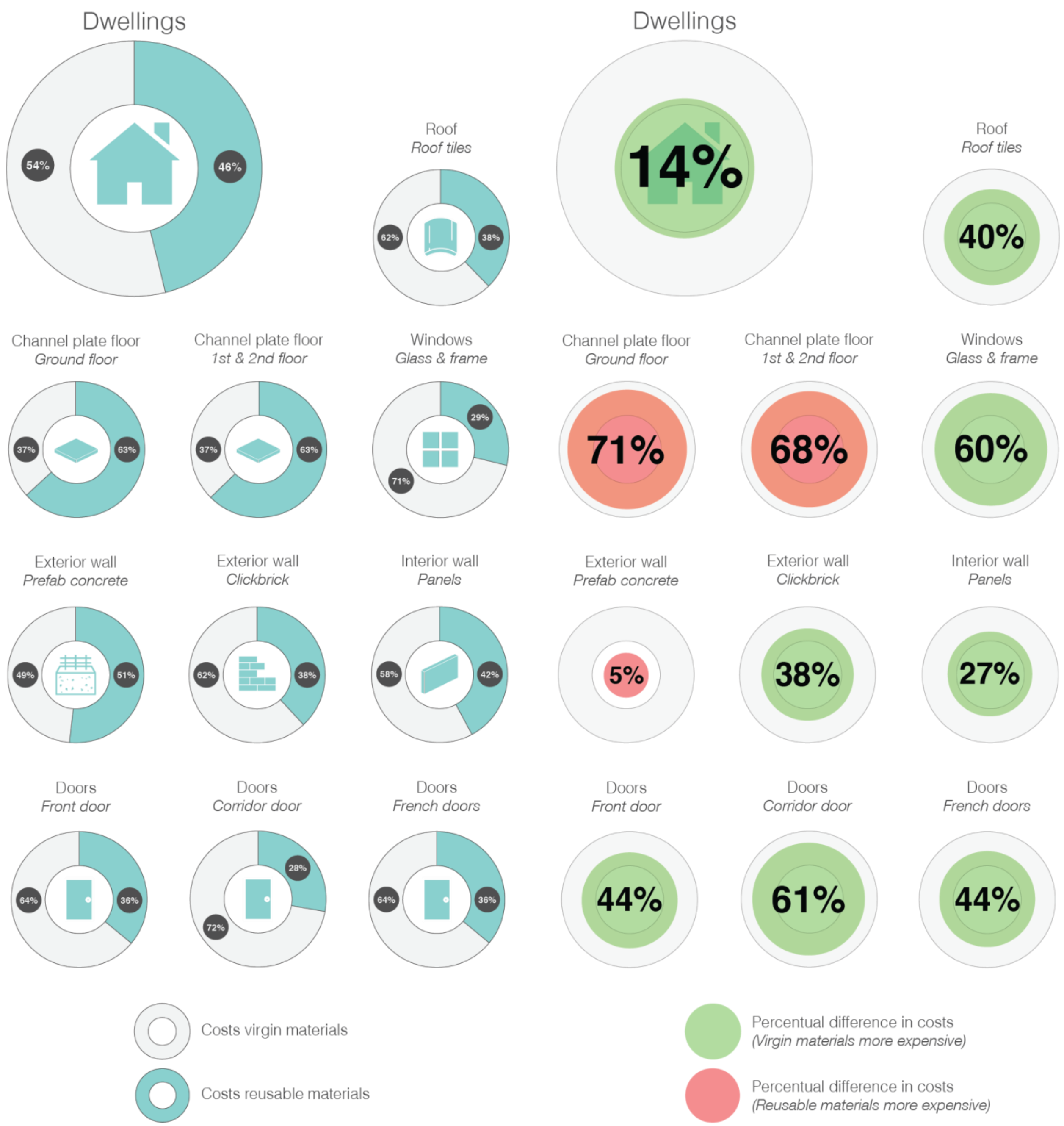


Table 4.2 Project-based model output (own table)

According to the input visible in Appendix 11.12, it shows that building dwellings with reusable materials has margin of 14% in total. This would mean, based on the number of reusable materials available, the three dwelling types as reference, the distance of the sources of the materials, the budget and the demand of dwellings by the client, it would be 14% cheaper to use reusable building materials compared to virgin building materials on a project-based scope. It is noticeable that three of the materials, which are the channel plate floors and the prefab concrete walls are more expensive when reused, while the rest of the materials are cheaper when reused in this comparison. Especially the floors, which are made out of heavier material, are much more expensive compared to virgin floors.

The results of the comparison depends on a lot of factors. Different assumptions are made to achieve these results and the framework used for the operational creates a large number of interesting topics for discussion. However, due to the framework which is used, the results provide a slightly misdirected vision on the possibilities on reusable building materials in new construction projects. The goal of this research is to reduce the usage of virgin materials and the findings of this model give insight in what numbers could be calculated in the given case. But the input of the case which is calculated and which delivered the numbers and costs that are presented in this chapter, are still hypothetical. The model could actually provide an influence in the construction industry, when the important aspects of this model are clearly evaluated and adopted into different scales. The model will definitely provide help in the transition to a more circular construction industry, when the framework is being increased in scale and context. The boundaries of the framework brought to this research and how the different aspects of the model responded to the boundaries are elaborated in chapter 5. Also, many follow up research ideas, such as recommendations for the different elements of the tool to be developed, other market parties or interesting strategies are discussed in chapter 7.

PART 5 DISCUSSION

As mentioned at the beginning of the research, operational research tries to solve complex real-life cases. In this research, the main focus is to discover how the usage of virgin building materials in new construction projects could be decreased. The results presented in the former chapter showed a difference in costs between reusable and virgin materials, the reusable materials in overall being cheaper. But, the choices made which resulted in this number is based on the chosen framework this research operates in. The following section discusses these factors, what influenced the decisions made and why some of the assumptions where made. Also, this chapter focusses on further development possibilities for the operational model, based on factors outside of the scope of the research. Finally, the process of the research is evaluated, eventually leading towards a final conclusion of this graduation thesis.

Figure 5.1 Discussion topics (own ill.)

The results of the project-based level calculation show that it is, in fact, cheaper to use reusable materials for new dwellings to develop. But, there are many factors that should be taken into consideration when stating the fact that reusable building materials are cheaper than virgin materials. If you would discuss this result with experts or companies in practice, most of the people would disagree or do not believe the validation of the calculation. This is partly because the construction industry is far more complex than the costs for just the building materials. To transform the entire structure of the construction industry, far more extensive research should take place and even when it is researched, due to the large scale and the many stakeholders within the construction industry, it would take years, even decades to transform the system. However, for this research, certain assumptions made within the scope of the reuse of building materials are discussed. The following sections provide four main topics of discussion, each related to the scope of the research and substantiated with arguments to take into account when stating the results mentioned in the former chapter.

5.1 TRANSPARENCY OF DATASETS

The first topic for discussion is a problem which makes the entire transition from the traditional concept of dwelling projects to reuse of building materials in a new projects much more difficult. There is a lack of transparency in the availability of reusable building materials. Even though there is so much material out there, ready to be reused, there is no clear overview of what the exact numbers, dimensions, quality and other specifications are. Another problem is the lacking of connection between demand and supply. There is a lot of material available, but also a lot of (re)-construction projects initiating. The connection should be made between the companies starting new projects and cases where materials are ready to be reused. This matchmaking should be taken place a lot earlier in new projects.

However, the problem is the competition between the different suppliers, which creates a barrier between demand and supply. The irony is that multiple organisations who are leaders in this transition are all about collaborating, sharing, transparency and other motivational speeches, but in reality, the construction industry is far from an integrated collaborating structure. During this research, the search for datasets from real-life cases turned out to be a real struggle. As mentioned in the description of the different possible input cases, section 3.3, there were many interesting partners to collaborate with, such as the EME-Platform, the Cinderela project or the Amsterdam Metropolitan Area. However, due to the fact that this research is part of the Technical University of Delft and consultant company Alba Concepts, partners hesitated and finally declined to share information as input. Most of this information contained privacy-related data, such as addresses and personalized information of participating companies.

For integrated models such as the operational model developed in this research to create actual insight into the feasibility of the project, there should be a change in sharing information and transparency of datasets. If so, there is much more information available that could be implemented in the model. This would create possibilities to develop models on the different levels of scale, which then could be compared to each other, to have a much larger overview of results, based on a much larger set of variables. The more variables, the more substantiated the results will be. When this model is used as an advisory tool to create insight for an organisation such as a municipality, the possibilities become much larger, meaning different types of dwellings could be built and much more materials will be reused. For now, the model is limited to hypothetical datasets, but if competition would be replaced by collaboration, it would be possible in the nearby future to produce real-life results.

5.2 REUSABILITY OF BUILDING MATERIALS

The second topic of discussion is related to the actual materials that will be reused. The six types of building elements, described in section 3.4.2, are divided into a set of materials which show potential to be reused or related to reference projects that showed whether or not the material could be reused. This list of materials is determined in collaboration with an expert colleague of Alba Concepts. However, the number of materials are chosen within a certain scope, while in fact much more of the building elements of dwellings should be reused. In this research, the final calculation shows the comparison between the costs of the reusable and virgin building materials, which can be reused. However, for an entire dwelling to be realized, much more materials are necessary. Looking at the layers of Brand (1994), the other layers, such as 'services', 'space plan' and 'stuff' are not taken into account in this calculation. If more information and techniques are used to deconstruct and preserve the other building elements, the list of to be used materials will be larger, thus creating more dwellings with almost completely reused materials. Looking at the materials of the dwellings that showed the potential for reuse for now, it covers a large area of the total square meters of material within the dwellings. The question could be asked how much of a difference it would make if the other materials, which are left out in the calculation due to the fact they do not have a high potential for reusability, are investigated to be reused as well. Would it be feasible?

The design process for the future of dwellings should be taken into account as well. The dwellings that provide the building materials coming from real-life cases are constructed in earlier periods. Every different construction period used different techniques, different materials within the buildings and especially different interfaces and connections. This makes it difficult to determine how much of the materials will be preserved when deconstructed. When reusability of materials will be the standard for new dwellings, the costs for deconstructing will decrease, making it much more interesting to reuse the materials of future dwellings. This instantly creates a larger list of materials to compare with the virgin costs. However, the techniques of detachable construction and circular dwellings is a must to improve the reusability of building materials and are further elaborated in the recommendations chapter.

5.3 VALIDATION OF FEASIBILITY

The main question of this research focusses on reducing the usage of virgin building materials in the future, which would results into a more circular construction industry. The feasibility of this transition plays an important role. The validation of the feasibility is thus an important topic for discussion. The results show a comparison between the costs for reused and virgin building materials, showing the difference in the costs for each type of material and also the costs per dwelling type. This quantity is based on the material costs, while in construction costs much more domains are a factor in the final budget estimation. Figure 5.2 shows which other costs could be taken into account as well. Indirect construction costs and additional costs are not directly influenced by the use of reused or virgin materials. However, processes that are traditionally being used for many years could change when reused materials are joining the process. Labour hours could increase because constructors are not used to the technique of construction these type of materials. Designers should adapt used materials within their dwellings, which would increase the duration of the design process, compares to standardized dwellings. The entire system of collaborating with materials will raise additional costs, such as operating costs, start-up costs, administrative costs et cetera. To calculate an entire project of creating dwellings with reused building materials, much more aspects of costs should be taken into account to create a complete, well-substantiated comparison of costs and the entire budget.

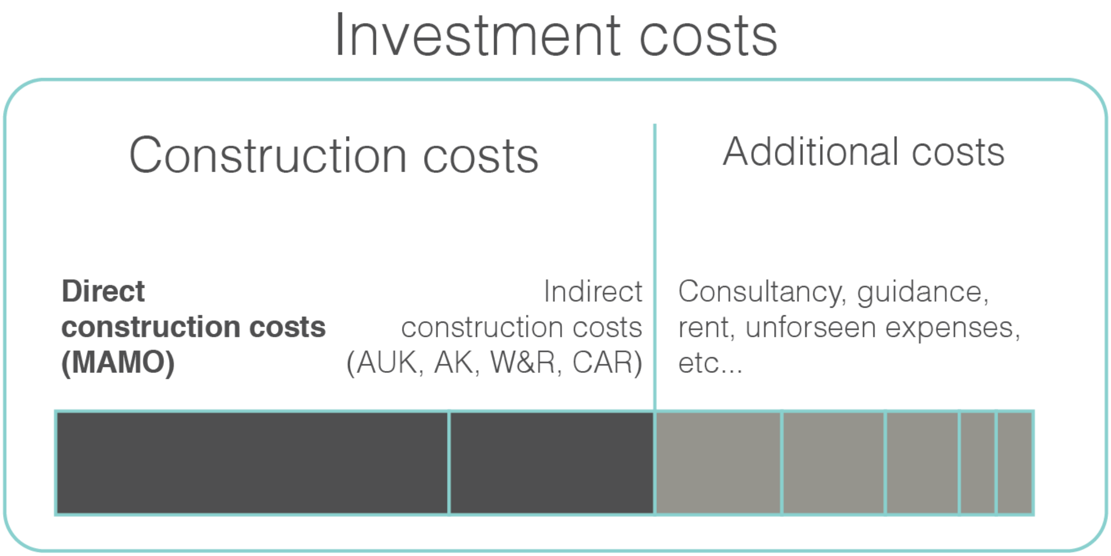


Figure 5.2 Investment costs of a construction project (Gemeente Amsterdam et al., 2017)

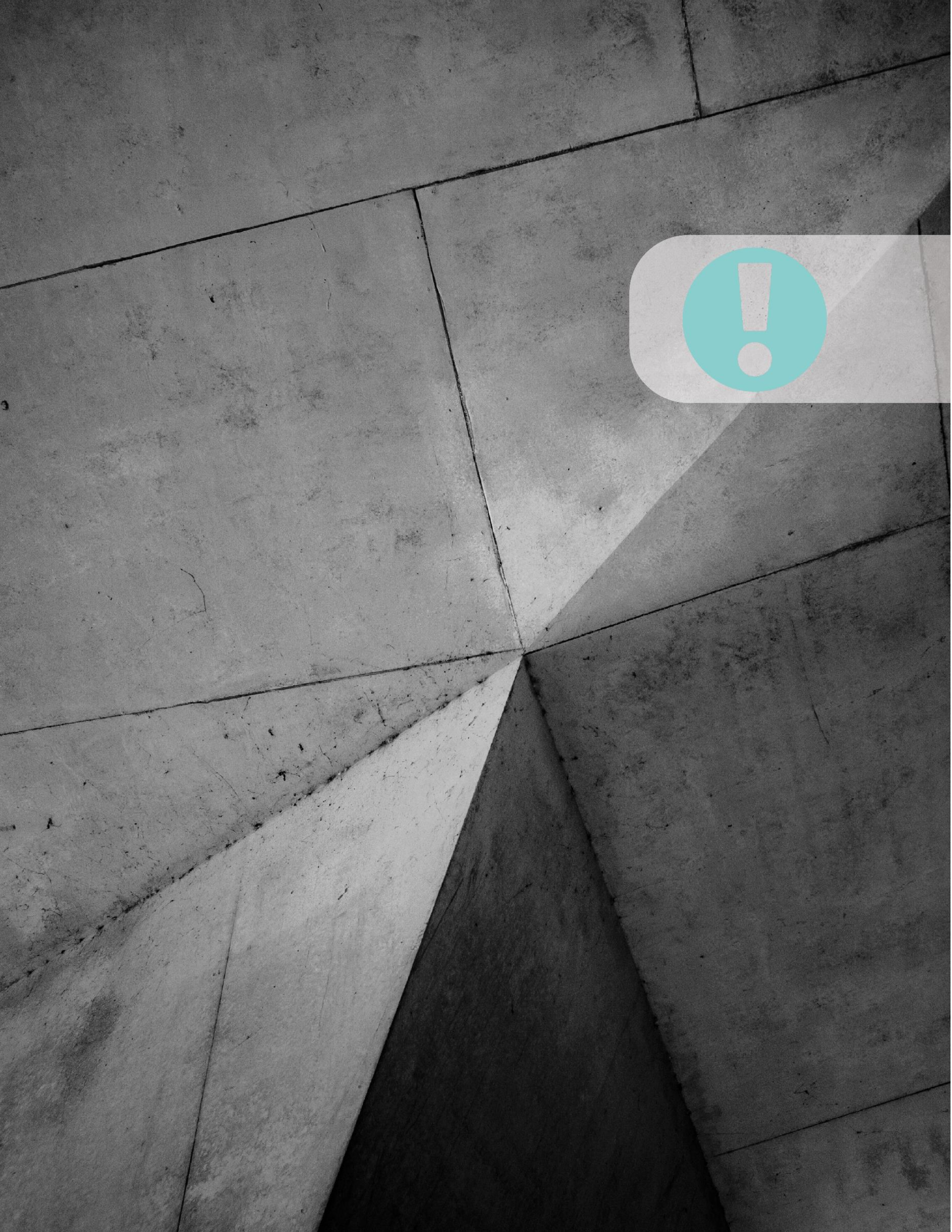
The costs for each material type are also up for discussion. The virgin material costs overview, which is visible in Appendix 11.9, is based on sources online. For example Cobouw Bouwkosten (Cobouw, n.d.) has been referred to many times. However, the source of costs for materials is different for each material. Most of the materials showed a certain amount of euro's per square meters, which description consists of a so-called recipe, showing an overview of all the factors and additional materials and processes which finally lead up to the costs per square meter. However, not all the materials are this well-defined, making it difficult to determine the actual material costs per square meter. Some recipes of materials describe besides the material costs also assembly and labour costs. To create a well-substantiated overview, a collaborating company, experts in construction costs, should provide an overview based on a singular database, where all the information of the different material are similar and based on the same sources.

The formula designed for reusable materials is probably the most interesting point of discussion. This calculation is not yet being used in practice and is an interpretation of different investigations of commodity valuations and factors of detachability and deconstruction. During the process of generating the formulas, through expert meetings and discussion with colleagues from Alba Concepts, the numbers where created. To actually validate the formulas, real-life projects with correct input are necessary to see if it would generate a realistic outcome. When tested and combined with a calculation of the different additional costs presented in Figure 5.2 it would show if it actually is interesting to use reusable materials in new dwellings. The formulas have been developed by focusing on a specific framework of factors, presented in section 3.5.2, and should be tested by example cases. These factors each have a different influence on the final calculation. Where the transportation factor is of a much lower influence compared to the external factors. The impact is much bigger, when looking at the increase in costs if materials has been damaged due to whether or pressure influences, or when the lifespan is much shorter. Also, when a material is hard to reach, the accessibility factor of the material is much lower, meaning it will be compensated in costs. The different influences these factors have are important for the realization of projects with reusable materials. It gives an overview for stakeholders which materials are interesting to reuse and which are not. When these formulas are being used in practice, it could affect the way we construct new dwellings and deconstruct old dwellings. The formula focusses in the moment on creating insight and making a comparison, showing the potential of the model when eventually being used in real-life. When applied in practice, the factors will develop and it will show how much influence the different aspects of the formula actually do have.

Not only the financial formulas of the costs for the building materials should be validated, the operational model should be validated as well. When design a model focussing on a certain context, it should be constantly tested and updated based on results from each test. As mentioned in section 3.1.3, in research through design it is important to always analyse the results and give feedback on the design steps taken in the development. But it is also of importance to analyse and develop the variables and constraints of the model. These factors react different when the model is setup in different ways, or when the input of the model is changing. It could much clearly show which variables and which parameters are of most influence in the results, which eventually results in a model which is tested in multiple setups. This validates the different aspects which are taken into account in the model. In the follow up of the process, the same numbers, both financial formulas and specifications of the chosen materials to reuse, should be tested in similar setups of the model, but based on the different levels of scale. When this has been checked, the results of the model are much more trustworthy. This could definitely increase the potential of implementing the tool into the practice of the construction industry. But if the tool is being further developed, validating the model with multiple steps is a necessary given.

5.4 INVOLVEMENT STAKEHOLDERS

Projects such as dwellings constructed with reusable structural materials to support the transition towards a circular building economy will never take off unless there is a significant amount of stakeholders involved within the process. However, it is yet to define in what phase of the project which stakeholders will be involved and how they are involved within which part of the calculation of the model. If the initiative comes from a municipal department, partners in the possession of datasets of building materials are necessary, but also companies who are willing to take on construction projects with reusable materials. To obtain the materials, there is a discussion of ownership of the materials. Also, the materials to be reused are probably still within their current dwelling, meaning a stakeholder should be involved to deconstruct the dwellings and transport the materials. Overall, these type of projects require multiple stakeholders, especially in the initiative phase, to get the project initiated. The model will be used as an advice tool, but when the possibilities of the model are projected on the demands of the client, the insight the model gives could motivate the client to get related stakeholders with sustainable ambitions involved. On the other hand, there should be a responsibility coming from the owners of buildings to be aware of the materials that are in their possession. Most of the larger companies who possess real estate or dwellings are not aware of their own setup of building elements within their buildings. There are external stakeholders who could make inventories of complete building stocks, but to really improve the circular economy, every owner of buildings should be up to date and aware of the available building materials. When this happens, transaction of buildings and collaborated projects will initiate much easier, because the datasets are up to date and easily shared between stakeholders. There will be a bigger responsibility for the owners, but it will result in much more collaboration and thus circularity of building materials.



PART 6 CONCLUSION

This chapter focusses on the conclusion of the research, by answering to the main and sub research questions, which are stated in section 1.2.3 and are described within the conceptual model. This conclusion focusses on the entire research, supported by the discussion and recommendations for further research, stated in the former chapter. The conclusion is described by answering each sub research question separately, concluding whether or not the research goal is achieved by answering the main research question.

6.1 SUB-QUESTION 1 FEEDBACK

The first sub-question of this research consists of the following:

What specifications are necessary for a case study to be implemented as input for the operational model?

During the research the three levels of scale were presented that divided the possible real-life cases into three different sizes of context. For every level of scale, a model setup was defined, which provided a dataset with a certain amount of specifications on the different materials implemented. However, to obtain the datasets of the case studies from the different partners, a large process was necessary to go through, which was based on a future collaboration. For the project-based model, the different case studies provided by Alba Concepts lacked the correct information and the collaboration of 'de Alliantie' never initiated due to financial problems. The possible collaboration on a region-based level with the 'EME-platform' had the most potential, but due to fear of sharing data because of the competition between similar material exchange platforms the data was never shared, which led to a dead-end, eventually using the hypothetical flow of information of the 'EME-platform' as a setup for the region-based model. The third input level, on an enterprise-based level, provided collaboration with the most potential, which was the 'Cinderela' project. This overview of material flows in the entire country could be the best input this operational model could be developed to, but due to the long-overdue process of contractual agreements between both parties the collaboration didn't get initiated. Even though, an enterprise-based model with input from the 'Cinderela' project has the most potential for future research to be developed, due to the completeness and accurateness of the system. So the third datasets could be the most optimal, but due to the difficult and underestimated process of obtaining the data, hypothetical datasets are used for the input of the operational model. When in the future datasets and case studies will be used as implementation for these typical kind of calculation models, it is important there is a clear definition of collaboration and data sharing between the stakeholders, internal and external.

6.2 SUB-QUESTION 2 FEEDBACK

The second sub-question of this research consists of the following:

What is the current demand in the construction industry for new housing projects?

There are many different dwellings that are standardized by the government. For this research and the operational model, three prototypes are analysed and presented in section 3.4.1. However, as mentioned, there are many more standardized dwellings that could be used as a demand for these type of projects (W/E Adviseurs, 2011). These could be implemented in the model as well. The demand depends on each different project on the context and the budget of the client. In general, as presented in section 2.6, multiple regions, especially in the Amsterdam Metropolitan Area, are in need of new dwellings. However, the main challenges lay within the design of the future standardized dwellings. As mentioned by Jim Teunizen, founding partner of Alba Concepts, circular construction projects with reusable materials integrated into new dwellings will be normal, way sooner than expected. So the demand for dwellings in the future is to adapt to the idea of reusable dwellings, which could be detached easily to lower the costs for reusable materials in the future, improving the life span of these materials and the reduction of waste and virgin building materials. The amount of materials which are analysed and taken into account in the operational model is relatively small, compared to the many materials which are available in a standardized dwelling. The different materials which haven't been taken into account in the calculation will be part of the future demand for new dwelling projects, as well as the techniques of how to implement the reusability of these materials.

6.3 SUB-QUESTION 3 FEEDBACK

The third sub-question of this research consists of the following:

How can a comparison between the overview of the cost of virgin and existing building elements for new dwellings provide a feasible business opportunity?

This question focusses on the feasibility of the project. The value of the comparison between virgin and existing building materials lays within insight which it gives to the client. The overview consists of the comparison of each different building materials, whether it is cheaper or more expensive. Clients can adapt their wishes to the results of the calculation. However, it also gives an insight on how to calculate the costs of reusable materials. The formula designed is innovative, based on recently developed calculations and validation factors. This formula should be tested in context, to get it validated. However, for now it shows the costs of the materials. As mentioned in the discussion and recommendations chapter, there are many more aspects of feasibility to take into account when calculating the costs of an entire dwellings project, which consists of reusable materials.

The second factor to take into account is the adaption of real-life context as input. When a client enters input in the interface of the operational model, certain variables are necessary, such as location, budget and demand for dwellings. However, also the supply of materials is an input of the client. The feasibility of the business case is being calculated and if the result is negative, different strategies are possible to build towards a feasibly business case, by for example only reuse building materials that are cheaper if reused or to use a different source. The quality of the comparison lays within the fact that it gives insight on which materials the project could benefit and how the model should be adjusted to realize the business case. The creation of the interface of the tool plays an important role when this model adapted into practice.

6.4 MAIN RESEARCH QUESTION FEEDBACK

The main research question of this research is:

How can an operational model link the supply of existing building materials with the demand for new construction projects in order to reduce the use of virgin materials and thereby improve circularity in the construction industry?

The main conclusion:

*By developing an operational model which calculates the **difference in costs** between the reused and virgin building materials, showing that the reusable materials are **cheaper** compared to the virgin materials, based on the given **framework**.*

This question generated the research goal of reducing the usage of virgin building materials in starting construction projects. Looking at the results of the project-based level operational model, it shows in the comparison in feasibility that the costs for reusable materials are cheaper compared to the virgin building materials. This resulted in an overview and insight for the hypothetical client of the project, which shows it is more interesting to invest in reusable materials compared to virgin materials. This could lead to a reduction in the usage of virgin building materials, which was the goal of the main research. Also, the final deliverable, which is the operational model, proves its functionality and showed insight within the solution space. It is developed with the possibility to implement different datasets, multiple variables and other factors. The qualities that the operational model presents show the value of the model for the construction industry.

With presenting this conclusion, a set of comments should be made to substantiate the statement listed above and the quality's that are related to the operational model. In the discussion chapter, the framework in which the results were executed is based on a set of assumptions that lead to a positive outcome of the comparison. This means that every context leads to a different result, so the numbers presented are purely to provide insight for companies or municipalities who would consider reusing building materials. To execute the project, much more research and additional variables are necessary to create a closed framework with a realistic outcome. These recommendations were presented in section 6.1. The supply should be realistic and based on real-life cases. The feasibility study should consider the costs that are not taken into account within this research, based on the investments costs overview of Gemeente Amsterdam et al. (2017).

PART 7 RECOMMENDATIONS

The construction industry is one of the most traditional sectors in the Netherlands. There is still a lot of space for development, innovation and transition towards a circular industry. The following section describes the recommendations for further development and research, based on this graduation thesis.

Even though the project-based operational model is being developed as a conceptual model for potential business cases, it has the potential to grow significantly. The number of factors that could be added within the formula for the linear programmed calculation is unlimited, so is the amount of solutions of dwelling types to create. Also, the input for different business cases could differ from small to extremely large. If the companies start using business models for similar projects, it could initiate a quick development of more extensive tools, interfaces, platforms and such. If there is a clear collaboration between IT companies, data suppliers and partners from the construction industry, these type of models could improve the construction industry concerning circularity at a rapid pace. An important notion to make is the validation of the operational model. It has to be validated as much as possible to test whether or not the model will work in reality. By downgrading the model to simple variables and focussing on checking each variable on its own, these type of operational models will become much more trustworthy and sooner applicable in real life projects and cases. When the system is checked on all the different constraints and variables in different contexts. It could have much more influence in the construction industry, compared to the development of the model in this research.

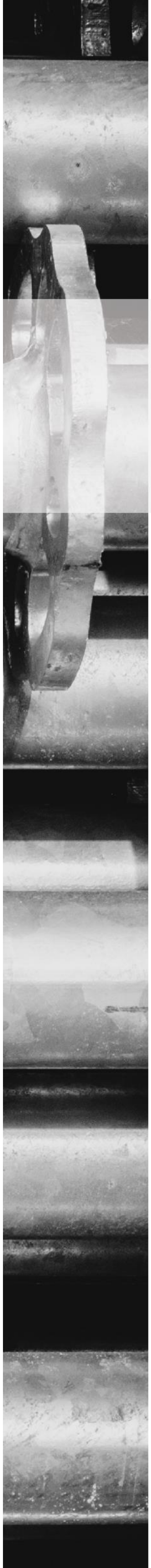
On the other hand, the system used for the operational model to run has its limitations. The 'What'Best!' add-in of Microsoft Excel is limited to its amount of variables to be used. To create the possibility to add more data in one immense model, the tool has to be updated or other systems have to be developed, which are easily accessible for construction companies and municipalities. Otherwise, traditional companies are easily returning to traditional building methods and virgin building materials. Also, the information of secondary raw materials could easily never be shared, due to fear of losing advantage in competition, but also due to privacy regulations. If the transparency of knowledge on available materials is not achieved, the possibilities for a typical kind of system to grow and connect the company's nationwide is probably a myth. So the technique behind the model should be updated.

The input for the model has a lot of potential as well. The collaboration with Cinderela could create an enterprise-based model with datasets from the entire country, which has a much larger scale, directly having a much bigger impact within the transition towards the CE. This directly results in advice for the government, reacting on the challenge of 1 million homes in the Netherlands and directly showing the potential of reusing a large number of materials within the country. The involvement and transparency of stakeholders are necessary to achieve such a large project.

On a smaller scale, there are also many possibilities to develop. As mentioned in the discussion, the dwellings should be designed to deconstruct in the future, creating much more supply. However, other markets to use the materials for are interesting as well, for example renovation. On a small scale, structural materials of historical quality could be preserved by reusing them in nearby, similar projects. This is a different market compared to new dwellings, but if there is enough demand this factor could be taken into account in a similar model as well.

The calculation in the project-based level example results in a positive outcome. However, if the numbers would be negative, different strategies could be taken for a municipality to decrease the costs of the reused materials. Every material shows if it is cheaper or more expensive. Clients can anticipate on the distinction of costs, by redesigning the dwellings. Development of the model is to create an insight that directly gives feedback on costs estimation of the different materials to be used. In this case, when a project is initiated, the client can adjust the different materials used and the different dwellings to build to a feasible solution. This interface could be designed or further developed in collaboration with a website or app designer, but based on the system created within this research. This tool could provide insight for clients such as a municipality or a housing client. The solve page presented in Appendix 11.12 would be the setup. The input would exist of the number of dwellings the clients want, the budget which is available and the preference for type of dwellings on locations.

The main message which is delivered by this research is the great potential of improvement of the construction industry. The potential is clearly visible in the different aspects of the construction processes, but most of the stakeholders involved are holding on to traditional processes. Due to fear of risks, losing money or uncertainty, most of the stakeholders aren't willing to implement circularity within the processes. This research shows there is definitely a lot possible to work with. The 14% shows the potential, reusable materials purely are cheaper when being used for new dwellings. But there are so many other aspects involved when developing building, which means much more research is necessary. This research could act as a pioneer, focused on the first step of the MAMO costs and encouraging other students or employees in the current area of construction to start researching the following aspects and implementing them as soon as possible into the traditional processes. The sooner the transition of rearranging these processes initiates, the sooner the construction industry will benefit from all the innovation which are about to be developed. Hopefully, the results of this research will trigger the construction industry to take research of reusable building materials and implanting them in the standardized construction processes to the next level.



PART 8 EVALUATION

The graduation process started a bit different compared to the regular first weeks of a graduation project. Instead of looking for a subject between the different departments, I've looked for a project that I could start with before the semester started. This provided some difficulties but also gave me a head start. The Joint Interdisciplinary Project at Royal HaskoningDHV directly gave me a subject to focus on. The project was going on for 10 weeks, full-time. Normally it is not possible because other courses should be taken during this period. However, it was possible to combine the courses with the internship. For future students who would pursue to do something similar, it is wise to research possibilities with the credits and courses still to take. Otherwise, it is not efficient to start your research graduation with such a large project. In my case, I discussed it with Professor and chairman of the Management in the Built Environment department Vincent Gruis and Master Coordinator of Management in the Built Environment Fred Hobma, which both agreed to the situation.

The second part of the graduation course was more difficult because the project for the first quarter ended. Instead of a clear objective, which Royal HaskoningDHV provided, there was no goal anymore and it felt as if the research stagnated. It was difficult to continue on the subject because there was no case it was connected to anymore. So in this period, it was key to find an internship where the rest of the graduation could be executed. From that point, it would generate more motivation to continue.

After the P2 presentation, I started the graduation internship at Alba Concepts at ‘s Hertogenbosch. Associate professor Hilde Remoy put me in contact with one of the partners and after two meetings we decided I could join the company to execute my master thesis. From the start of the internship, the idea was developed that my thesis would collaborate with an organisation in Amsterdam, the Excess Material Exchange Platform. During the first few months, the process of setting up the collaboration between the EME turned out to be a struggle. Both parties couldn’t agree on a collaboration, not willing to share data with a graduate student which was connected to a University, fearing the data would leak. It showed the sensitivity of the practice on innovation, but also the underestimated vision I had on obtaining these datasets. There was too much risk apparently to share data, which eventually led to a shutdown of the collaboration. This turned out to be a setback in the progress of the research and the development of the model. After a final determination of the collaboration, other projects were becoming an option for the use of the model. One of those options was a possible collaboration with de Alliantie. This housing corporation would start a project where archetypes within their portfolio would be analysed, which would create perfect datasets to use as input for my model. Unfortunately, the project never started due to financial problems at de Alliantie. Finally, in consultation with my graduation councilors, we decided to focus on the output and the calculation of the model and use hypothetical datasets, but with the notion that datasets are necessary for the validation of future projects.

The main lesson learned from this experience is the fact that innovative projects within large sectors such as the construction industry take much more effort to accomplish the correct components. Large projects never go exactly as planned from the beginning, which means that during the graduation process events will happen which push you of the track and you need to adapt to the changes. Working with multiple partners makes you dependent on third parties, which means it will not always go as you expect. The setback I've had due to the fact datasets were not shared with me meant I had to change my research setup and perspective towards a final achievement. It is important to realize during the process what value can be taken out of the data you actually can attain and how you use this data.

The graduation company provided me with a lot of experience on this subject from practice and provided me with multiple datasets, such as example projects, expert panels and multiple discussion with colleagues, internal and external. The value of a company that supervises you during a graduation process is a must-have for a project that directly connects with the demand in the practice. The choice to be part of Alba Concepts took this research to the next level.

PART 9 REFLECTION

Within the field of operational research, the main objective is to solve real-life problems. Within the transition towards a circular construction industry, the main objective in this research is to reduce the usage of virgin building materials. However, the challenge to complete the transition and make the entire industry of construction circular is much and much bigger. Though there is many literature already produced on these topics. The final chapter of this graduation thesis reflects the current literature and how this research adapts to the existing publications.

The literature that describes the operational research methods, published by Barendse et al. (2012) which has been used for most of the references and the development of the operational model, is a substantiated report of the technique of operational research, how it can be applied to design solutions and to solve problems. The course, which is lectured at the second year of the Management in the Built Environment master at the Faculty of Architecture and the Built Environment, has the mission to teach methodological concepts, research methods and problem solving methodologies that can be applied by students for their master thesis (Barendse et al., 2012). The reader, which the students use during the course, lacks of example graduation projects to explain schematically how the model is interpreted. This graduation thesis could supply an example project on how the model is developed, which variables and constraints have been used and how the formulas and systems are being linked to the 'What'sBest!' add-in for Microsoft Excel. This technique also showed its limits, due to the maximal amount of variables that could be used when the trial version of the add-in is used. This thesis provides an example of the possibilities within operational research and could give students more insights in how to execute an operational related graduation thesis.

In the development of the calculation of the costs for the reusable building elements, literature has substantiated the factors that influenced the final outcome of the total costs per material. The LI (losmaakbaarheid) factors are based upon the development of the BCI (Verberne, 2016), which is developed by Alba Concepts. Earlier within this research, it has been mentioned that an important innovation within the building sector is creating a substantiated universal language of the terms of the different layers of materials, elements and products. Within practice, as mentioned by multiple colleagues of Alba Concepts, the discussion on the different levels of definition is still ongoing. There is still no universal language that states when a material is a material, an element is an elements and a product is a product. Within this research, the building materials and elements are referred to a lot and used consistently within naming of definitions. A material consists of a certain recourse, while building elements consists of set of materials. This covers almost all the different building elements, meaning that for some building elements the discussion continues whether or not it is an element or a material. This research reflects on the use of these terms and provides a structure that could be applied, but it depends on future research if it eventually will.

The third topic reflected on the literature is the matter of factors that influence the formula of reusable building materials. The literature consist of mostly existing formulas developed by Madaster et al. (2018), but they haven't been tested in real-life projects yet. They are still under construction. The transportation and deconstruction calculation has been implemented in this research, with some minor adjustments. This research gives an overview of the outcome of these calculations and can provide feedback on the validation of the formulas. Of course the data input within this research is hypothetical as well, but the formula has been added to the complete overview of costs for reusable materials. When the other pieces of the puzzle are reflected as well, Madaster et al. (2018) could use the results of the operational model developed for future development of determining the value of reusable materials. The external influences calculation could be added within the development of Madaster et al. (2018) as well, but first the model has to be tested with real-life cases to validate the formulas developed. When connected, this research could bring a lot of pieces of the puzzle in adding value to reusable materials in new construction projects together, thus supporting the transition towards a circular construction industry.

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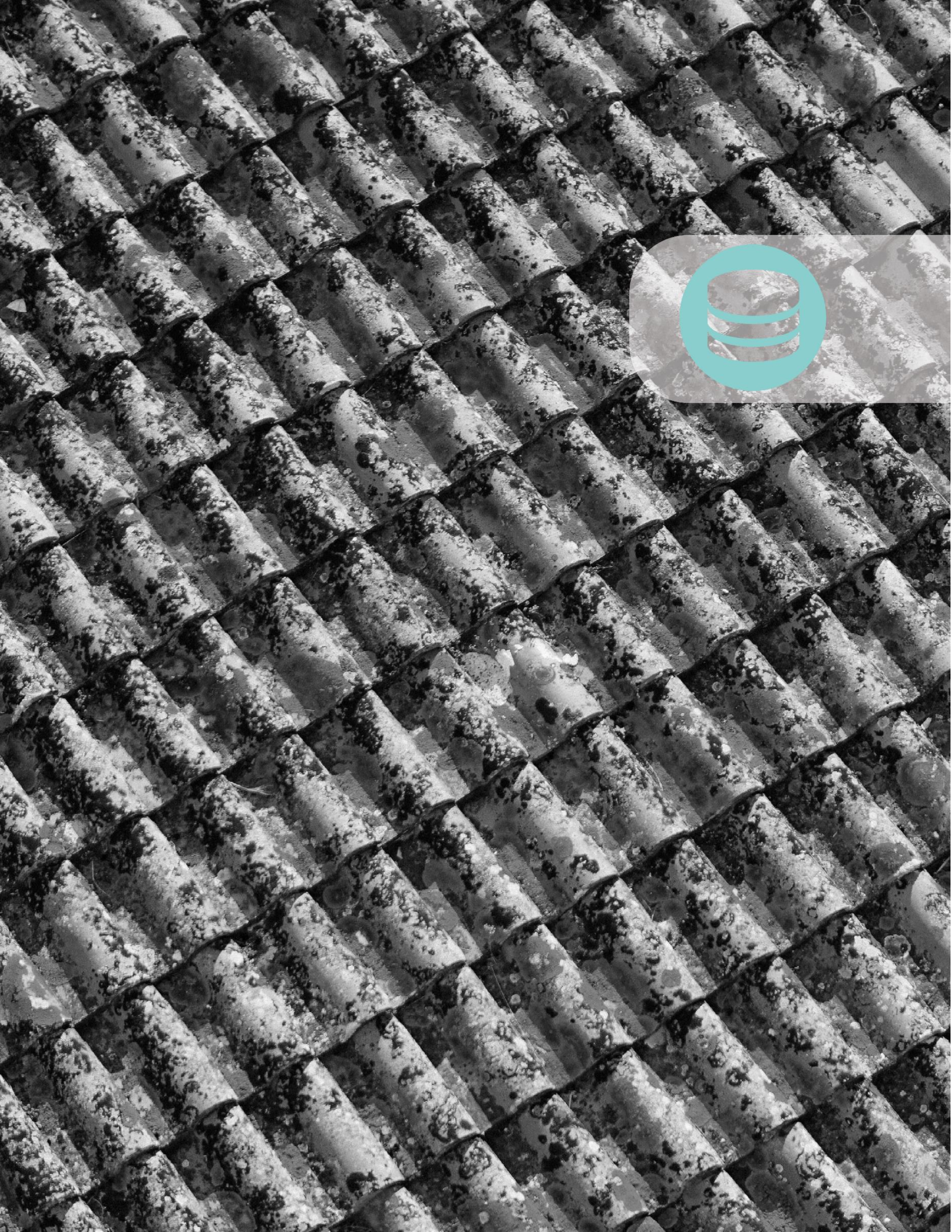
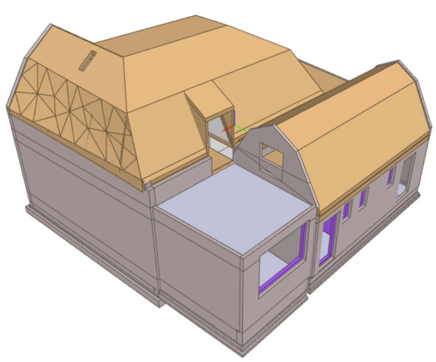


PART 11 APPENDICES

11.1 APPENDIX A: DATA SINGLE DWELLING 'VIIA PROJECTEN'

	Building element	#
0		8
1	Basic Wall:13_RHD_brick_220	16
2	Basic Wall:13_RHD_brick_50	8
3	Basic Wall:13_RHD_brick_55	14
4	Basic Wall:13_RHD_brick_65	4
5	Basic Wall:13_RHD_brick_70	21
6	Basic Wall:16_RHD_brick_220	16
7	Basic Wall:21_RHD_brick_110	10
8	Basic Wall:21_RHD_brick_220	17
9	Basic Wall:21_RHD_wood_plain_16-50-16	4
10	Basic Wall:22_RHD_HSB_50x55 hoh 400_2x gipsum_12.5	6
11	Basic Wall:22_RHD_HSB_50x75 hoh 400_2x gipsum_12.5	8
12	Basic Wall:22_RHD_HSB_50x85 hoh 400_2x gipsum_12.5	3
13	Basic Wall:22_RHD_HSB_Pui_110	2
14	Basic Wall:22_RHD_brick_110	5
15	Basic Wall:22_RHD_brick_200	1
16	Basic Wall:22_RHD_brick_220	1
17	Basic Wall:22_RHD_concrete_foamed_100	9
18	Basic Wall:22_RHD_concrete_insitu_100	4
19	Floor:13_RHD_brick_foundation_slab_100	4
20	Floor:13_RHD_brick_foundation_slab_315	1
21	Floor:13_RHD_concrete_insitu_foundation slab_100	1
22	Floor:23_RHD_beam system wood_50x120 hoh 600 + vloerdelen 25mm	1
23	Floor:23_RHD_beam system wood_60x175 hoh 920 + vloerdelen 25mm	1
24	Floor:23_RHD_beam system wood_70x230 hoh 660 + vloerdelen 25mm	2
25	Floor:23_RHD_beam_system_wood_55x175 hoh 1000 +wood_22	1
26	Floor:23_RHD_concrete_insitu_120	2
27	Floor:23_RHD_concrete_insitu_130	1
28	Floor:23_RHD_concrete_insitu_150	1
29	Floor:23_RHD_concrete_insitu_65	2
30	RHD_concrete_insitu_reinforced	1
31	RHD_stone_brick	1
32	RHD_wood_45	12
		188

Figure 11.1 Data single dwelling (HaskoningDHV, 2018)



11.2 APPENDIX B: OPERATIONAL MODEL EXAMPLE

This Appendix explains the operational model created for the JIP and the graduation research. A notion which should be made about this explanation is the fact that the model and the results are not final yet. This is just a setup of the model and an elaboration of how the model works and finally should work. The model is also used for the course Operations Research Methods (AR3R058).

11.2.1 MAIN CLIENTS AND GOALS

The goal is to optimize the use of materials gathered by urban mining into new housing projects. The number of materials gathered by the data supplying company, Royal HaskoningDHV, are available for this model. It contains information about many existing buildings in the province of Groningen, which mostly are endangered by the earthquakes because of the gas extractions. The municipality of Groningen, which is the direct client and so the main stakeholder of this project, is overall working together with companies such as Royal HaskoningDHV to tackle the endangered living situations (Figure 11.2). Most of the projects concern renovation and reconstructing, but the process of new earthquake resisting buildings is a subject where urban mining comes into action.

Figure 11.2 Main stakeholders, Royal HaskoningDHV (contractor) & Municipality of Groningen (client)

For the upcoming housing projects within the Groningen area, the usage of current building materials of the endangered buildings could be an efficient and circular option. The goal of this model is to research how to optimize the use of the materials gathered from the current buildings into the new projects (Figure 11.3). Eventually, this would help to achieve the goal of reducing the usage of virgin materials in housing projects.

What is the best division of materials used, which materials are possible for reuse and how do you define the different types of buildings which could be built mostly out of old materials? During the setup of this model, there is an ongoing decision-making process about which of the chosen elements should be maximized or minimalized.

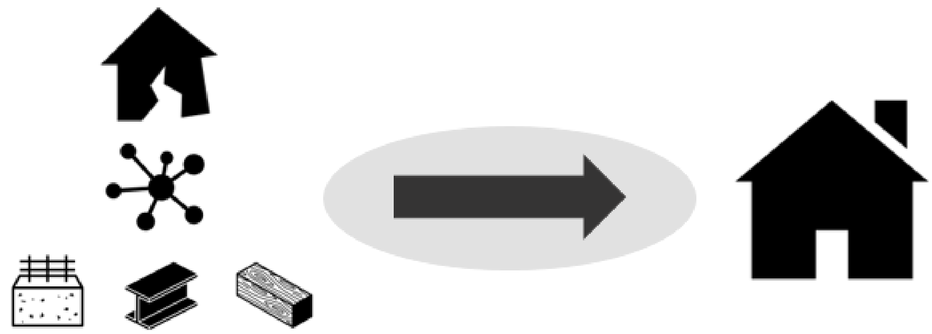


Figure 11.3 Research goal (own ill.)

11.2.2 MATHEMATICAL ELEMENTS

When setting up the design model, certain variables and constraints must be determined to define the limitations of the model. The data, provided by Royal HaskoningDHV consists of an overview of buildings and the materials of which the dwellings consist of. The database is designed as an output of .ifc and .json files, which are the type of files provided by Royal HaskoningDHV. In the database overview, all the materials in the buildings have been inventoried. The amount of building materials what is delivered by Royal HaskoningDHV depends on the amount of building files which are available. In the setup of this model, a total of 7 buildings are used for the input. The overall amount of these materials will be used as the constraints for the model. In Appendix 11.1, an overview a single house and the total overview of all the materials used for this dwelling are shown. To make the model more realistic, the number of houses used for the model has been multiplied by 100 times, which gives more materials to use for the possible optimization.

The constraints for the model exist of different building elements, such as walls, floors, and beams. The type of material which these elements consists off differ, but for this model, the four most common materials have been chosen to use as input for the linear programming. The chosen materials are wood, concrete, steel, and bricks (Figure 11.4). In the model, these constraints are mentioned as recovered materials.
The variables are the different building elements which are necessary to build a new house. The list of elements needed is much longer for a house to have it completely functioning, but for this model, the three main building elements have been chosen as variables. As mentioned earlier, the chosen building elements are walls, floors, and beams (Figure 11.5).

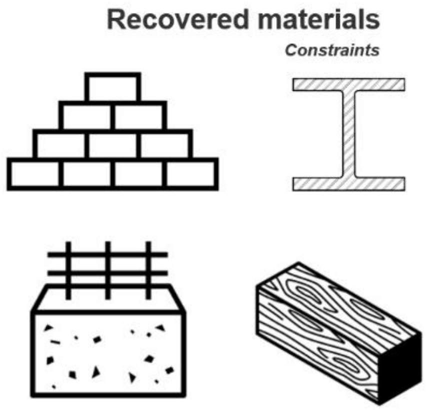


Figure 11.4 Recovered materials (own ill.)

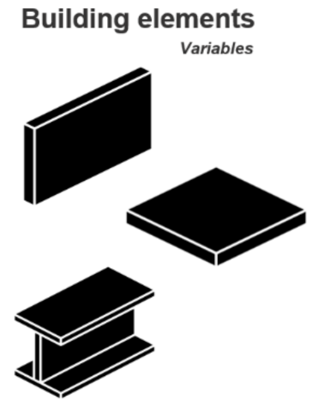


Figure 11.5 Building Elements (own ill.)

11.2.3 MODEL INPUT

The variables and constraints for the model have been mentioned in the previous chapter. These will assist to formulate the input for the model. The goal of the model is to find the most optimal division of material to build new housing projects. So, for the input of the model, first, the different possibilities of houses should be defined. Within a city, there are a lot of different types of building, from residential to business to public buildings. To design the buildings in the model in a real sense and to listen to the client's wishes, this model focusses on three different types of residential buildings, which are apartments, terraced housing and detached housing. Figure 11.6 shows an example of existing houses within Groningen, along with the number of square meters per house, the number of

Figure 11.6 Dwelling types and information (Funda)

rooms and the costs of the dwelling, when to be bought. The information of the example dwellings has been derived from different ads at https://www.funda.nl/.

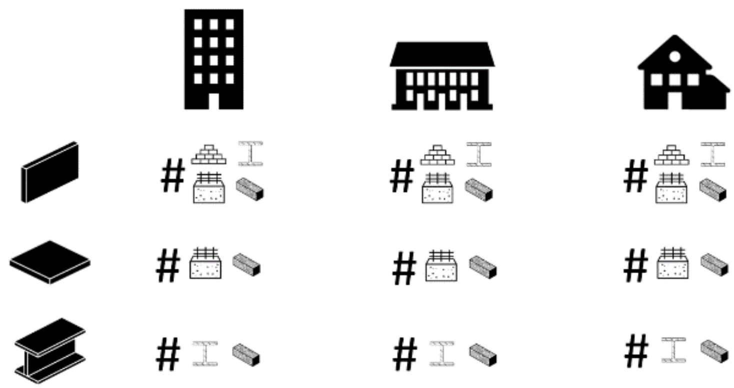
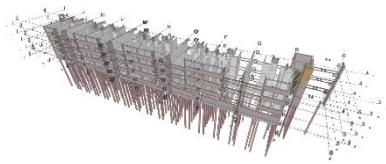


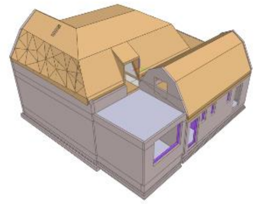
Figure 11.7 Conceptual definition of dwelling design (own ill.)

These conceptual new housing projects, which are another variable to control, demand a certain amount of building elements (variables) of different materials (constraints). One of the tasks to regulate the input of the model is defined the amount of each element required, to design three different dwellings from scratch. In Figure 11.7, it shows the division of materials per building element made which is used for the model. For every different dwelling type, a different amount of building elements is defined, which provides the input for the model.

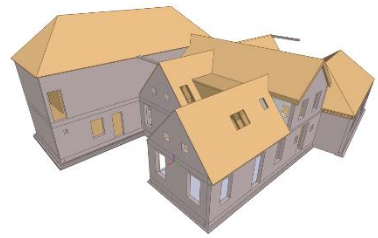
Each dwelling consists of a different amount of building elements and materials. To operationalize the research question and simplify the model, each dwelling types has a certain amount defined, based upon example projects provided by Royal HaskoningDHV. Table 1 shows three example buildings, which division of elements provides the amounts used for the definition of the dwellings. These three dwellings are existing buildings, located somewhere in Groningen. Because of privacy legislation, the actual location of these dwelling remains unknown. The input which is shown within Table 11.1 is not the final numbers yet. They are still in the process of being defined and will be changed during the ongoing graduation project. For the explanation of the model, the following numbers will be used which are previewed in table 1. Every value presents a possible number of elements of a specific material necessary to build the dwelling. The numbers are interchangeable, depending on the qualities of dwelling the client wants.



Type A: Apartments



Type B: Terraced housing



Type C: Detached housing

Walls	Existing data *(*100)*	Type A: Apartments	Type B: Terraced housing	Type C: Detached housing
Bricks	178700	40	121	137
Concrete	121500	200	30	30
Wood	25000	10	35	46
Floors				
Concrete	43800	100	25	20
Wood	5400	5	20	12
Beams				
Steel	50000	80	40	60
Wood	50000	50	100	150

Table 11.1 Overall input operational model (own ill.))

11.2.4 MODEL DESCRIPTION

The input of the model is defined in section 11.2.3. An example of the data of building elements and materials of a single dwelling used for the model is visible in Appendix 11.1. The "What'sBest!" method within Microsoft Excel, will solve the model which is visible in Table 11.2. This screenshot is a direct outcome of the input which is shown in Table 11.2above.

	Amount of houses able to build			Amount of Wall elements used			Amount of floor elements used		Amount of beams used				
Dwelling types	Type A: Apartments	Type B: Terraced housing	Type C: Detached housing	Bricks	Concrete	Wood	Concrete	Wood	Steel	Wood			
Outcome	387	84	148	45976	84432	13633	43800	5400	43238	50000			
Objective function				1	1	1	1	1	1	1	286479,8797	Max!	
Walls											Constraint form	Sign	RHS
Brick for dwelling type A,B,C	-40	-121	-137	1							0	=	0
Concrete for dwelling type A,B,C	-200	-30	-30		1						0	=	0
Wood for dwelling type A,B,C	-10	-35	-46			1					0	=	0
Amount of existing brick				1							45976	<=	178700
Amount of existing concrete					1						84432	<=	121500
Amount of existing wood						1					13633	<=	25000
Floors													
Concrete for dwelling type A,B,C	-100	-25	-20				1				0	=	0
Wood for dwelling type A,B,C	-5	-20	-12					1			0	=	0
Amount of existing concrete							1				43800	=<=	43800
Amount of existing wood								1			5400	=<=	5400
Beams													
Steel for dwelling type A,B,C	-80	-40	-60						1		0	=	0
Wood for dwelling type A,B,C	-50	-100	-150							1	0	=	0
Amount of existing steel									1		43238	<=	50000
Amount of existing wood										1	50000	=<=	50000

Table 11.2 Operational model Excel (own ill.)

The model calculates the optimal amount of dwelling types (A, B and C). In the formula, the number of dwellings will be put down as NA, NB and NC. It also calculates the number of materials used for each building element. If we, for example, take the brick walls, we will define the total amount of brick walls used Mbw. The mentioned amount of materials needed for every building element of every dwelling type, visible in table 8.1, will be mentioned as b, in the case of bricks. The number of brick walls needed for example for dwelling A will be mentioned as b1w.

The model calculates the total amount of the different materials used and generates the amount of the three dwellings types to build. The total amount of for example bricks walls is determined by the number of dwelling types (A, B and C) and the required amount of bricks walls for each dwelling type. This gives the following equation:

$$M_{bw} = b_1w * N_A + b_2w * N_B + b_3w * N_c$$

There is a maximum of material to consider while calculating this model, which is the building elements available for every material. In the case of brick walls, the restriction regards to the maximum amount should be mentioned as:

$$M_{bw} \leq b_{ow}$$

The restriction is mentioned in the rightest column of the model for each material.

The same formula could be repeated for the following elements with the adjoining variables:

- *Brick walls:* M_bw
- *Concrete walls:* M_cw
- *Wooden walls:* M_ww
- *Concrete floors:* M_cf
- *Wooden floors:* M_wf
- *Steel beams:* M_sb
- *Wooden beams:* M_wb

11.2.5 MODEL OUTPUT

In the outline of Table 11.3, the specific results of the first example are shown. For this example, the input of Table 11.1 is used. It shows in blue the number of houses which are possible to build with the number of materials of different elements used. The sum-product of the results shows the maximum output of this equation. It calculates the maximum output of both the materials and the number of houses able to build. In this case, mostly apartments will be built and all the concrete and wooden floors are used for the construction of the houses.

	Amount of houses able to build			Amount of Wall elements used			Amount of floor elements used		Amount of beams used			
Dwelling types	Type A: Apartments	Type B: Terraced housing	Type C: Detached housing	Bricks	Concrete	Wood	Concrete	Wood	Steel	Wood		
Outcome	387	84	148	45976	84432	13633	43800	5400	43238	50000		
Objective function				1	1	1	1	1	1	1	286479,8797	Max!

Table 11.3 Operational model results (own ill.)

The results in Table 11.3 are just one of the multiple outcomes trying to make the model work. Also, the input is constantly changing, depending on what amount of materials are available. It is important to notice what the different inputs deliver as results and to keep track of the different possibilities within the project.

11.3 APPENDIX C: HYPOTHETICAL CONSTRAINTS INPUT REGIONAL-BASED MODEL

Constraints:

- Incoming materials in building sector, waste from other projects. List of materials in the building sector which could possibly be used within the model:

Material	Group
Isolation	Internal Wall
Steel	Structural
Concrete facades	External wall / façade
EPDM Roofing	Roofing
Sand-lime bricks	Internal Wall / Structural
Aluminum	External wall / façade
Concrete	Structural
Cement	Structural
Glass	External wall / façade
Plasterboard	Internal Wall
Stucco	Internal Wall
Bricks	External wall / façade / structural
Isolation material	Internal Wall
Laminate flooring	Flooring
Carpet	Flooring
Floor tiles	Flooring
Wood	Structural
Styrofoam	Internal Wall
Plastic	Structural
Roof tiles	Roofing

Costs

- Processing
- Transportation
- Demolition
- Implementation

Revenues

- From adjoining companies
- For each matchmaking

Groups of types of building materials

Internal Wall	Isolation Sand-lime bricks Plasterboard Stucco Isolation material Styrofoam
External wall / façade	Concrete facades Aluminum Glass Bricks

Structural	Steel Concrete Cement Bricks Wood Plastic
Roofing	EPDM Roofing Roof tiles
Flooring	Laminate flooring Carpet Floor tiles

Table 11.4 Groups of type building element and material (RoyalHaskoningDHV, 2018)

11.4 APPENDIX D: EXAMPLE DATASET STRUCTURE ALBA CONCEPTS

Project Project Doen! Renovatie Westelijk stationsgebied
Titel Inventarisatie hergebruik SPW 30 Arnhem
Datum 3-dec-18
Auteur BJS
Versie 2.0

Afvalstrategie (Ladder van Lansink)	
B	Hergebruik
C	Recyclen
E	Storten

Conditie	
1	Goed
2	Gemiddeld
3	Laag

Opmerking: De maatvoering betreft een indicatie.

nr.	Onderdeel	Toelichting	Foto	Materiaal	Afvalstrategie	Conditie	Demontage	Afzetmogelijkheid	Aantal (st)	Lengte (mm)	Breedte (mm)	Hoogte (mm)
Bouwkundige werken												
Fundering												
Skelet												
27	Daken (skelet)											
	Dakraam / lichtkoepel		86		Hergebruik	Gemiddeld	-	-	1			
	Glazenwas installatie		87		Hergebruik	Onbekend	-	-	3			
Dakafbouw/dakafwerking												
37	Dakopeningen											
	Zonwering lichtkoepel		88a	Metaal	Hergebruik	Goed	-	-	1			
Gevelafbouw/gevelafwerking												
31	Buitenwandopeningen											
	Kozijn vluchtdeur	Brandwerend	14	Hout	Hergebruik	Goed	0	0	1		1.263	2.500
	Vluchtdeur	Brandwerend	15	Hout	Hergebruik	Goed	+	+	1		1.135	2.350
41	Buitenwandafwerkingen											
	Gevelpui	Ter plaatse van entree	104	Aluminium	Hergebruik	Goed	+	0	1		5.398	2.474
	Gevelpui	Ter plaatse van entree	105	Aluminium	Hergebruik	Goed	+	0	1		2.780	2.196
	Gevelkozijnen				Recyclen	Gemiddeld	0	-	n.t.b.		divers	divers
Binnenwandafbouw/ binnenwandafwerking												
42	Binnenwand afbouwconstructies											
	Kozijn pui		50	Staal en glas	Hergebruik	Goed	+	+	1		6.580	2.034
	Kozijn pui		58	Hout en glas	Hergebruik	Goed	+	+	4		640	2.537
	Kozijn pui		59	Hout en glas	Hergebruik	Goed	+	+	2		1.955	2.537
	Metal stud scheidingswand	1e t/m 6e verdieping			Recyclen	Gemiddeld	-	-	n.t.b.			
32	Binnenwandopeningen											
	Binnenkozijn wandraam		1	Hout en glas	Hergebruik	Gemiddeld	+	+	1		1.453	2.190
	Dubbele binnenkozijn deur		2	Hout	Hergebruik	Gemiddeld	+	+	1		1.770	2.162
	Deur		3	Hout	Hergebruik	Gemiddeld	+	+	1		850	2.110
	Deudranger	Merk Dorma	16	Aluminium	Hergebruik	Goed	+	+	115			
	Deurklem	Positie wand	17		Hergebruik	Goed	+	0	2			
	Kozijn deur	Brandwerend	28	Hout	Hergebruik	Gemiddeld	0	0	1		1.015	2.055
	Deur	Brandwerend	29	Hout	Hergebruik	Goed	+	+	1		870	1.970
	Kozijn deur	Toiletdeur	115	Hout	Hergebruik	Gemiddeld	0	0	57		920	2.165
	Deur	Toiletdeur	115	Hout	Hergebruik	Goed	+	+	57		825	2.110
	Binnenkozijn wandraam	Veiligheidsglas	33	Hout en glas	Hergebruik	Gemiddeld	+	+	4		4.286	2.273
	Binnenkozijn wandraam	Veiligheidsglas	34	Hout en glas	Hergebruik	Gemiddeld	+	+	4		2.630	2.413
	Deurkozijn met zijlicht	Veiligheidsglas (14 per verdieping)	35	Hout en glas	Hergebruik	Goed	+	+	40		1.297	2.180
	Deur		36	Hout	Hergebruik	Goed	+	+	40		825	2.110
	Kozijn deur		41	Hout en glas	Hergebruik	Gemiddeld	+	+	6		1.000	2.160
	Deur vluchtroute	Maatvoering raam: b430 en h305	42	Hout	Hergebruik	Goed	+	+	6		920	2.011
	Deurkozijn met zijlichten		45	Hout	Hergebruik	Gemiddeld	+	+	20		1.773	2.266
	Deur		46	Hout	Hergebruik	Goed	+	+	20		920	2.216
	Deurklem	Positie vloer	47		Hergebruik	Goed	+	+	1			
	Kozijn deur		51	Hout	Hergebruik	Gemiddeld	+	+	16		1.773	2.160
	Deur		51	Hout	Hergebruik	Gemiddeld	+	+	16		910	2.110
	Kozijn deur	Beschadigd door constructieve balk	52	Hout	Hergebruik	Gemiddeld	+	+	4		2.359	2.551
	Schuifdeur kozijn	t.h.v. wenteltrap, veiligheidsglas (b=820, h=590)	54	Hout	Hergebruik	Gemiddeld	0	-	1		820	590
	Schuidfeur	t.h.v. wenteltrap	55	Hout	Hergebruik	Goed	+	+	1		1.015	2.085
	Deurdranger schuifdeur	Elektronisch	56		Hergebruik	Goed	+	+	2			
	Kozijn deur		65	Hout	Hergebruik	Gemiddeld	0	0	2		3.001	3.287
	Deur	Glas b=600 en h=985	66	Hout en glas	Hergebruik	Goed	+	+	6		930	2.012
	Kozijn deur		67	Hout	Hergebruik	Gemiddeld	0	0	7		2.050	3.287
	Kozijn deur		68	Hout	Hergebruik	Gemiddeld	0	0	7		2.500	3.287
	Schuifwand	Breedte panelen = 3830	69		Hergebruik	Gemiddeld	+	+	1		4.172	4.050
	Gevangenisdeur	Verzwaarde deur	70	Hout	Hergebruik	Goed	+	+	7		1.010	2.019
	Kozijn gevangenisdeur	Verzwaarde deur	71	Hout	Hergebruik	Goed	+	+	7		1.060	2.079
	Kozijn deur		72	Hout	Hergebruik	Gemiddeld	0	0	3		1.800	2.480
	Deur	b=600, h=985	73	Hout en glas	Hergebruik	Goed	+	+	3		930	2.110
	Kozijn deur		77	Hout	Hergebruik	Gemiddeld	0	0	2		3.752	2.475
	Deur		78	Hout en glas	Hergebruik	Goed	+	+	2		925	2.110
	Kozijn deur		79	Hout	Hergebruik	Gemiddeld	0	0	2		4.050	2.475
	Hang en sluitwerk		80	RVS	Hergebruik	Goed	+	+	2			
	Hang en sluitwerk		81	RVS	Hergebruik	Goed	+	+	2			
	Schuifdeur (automatisch)	hoogte deur h=2206	83	Aluminium	Hergebruik	Goed	+	0	1		2.695	2.527
	Kozijn deur		88	Staal	Hergebruik	Gemiddeld	0	0	55		1.375	2.655
	Deur		89	Hout	Hergebruik	Goed	+	+	55		920	2.216
	Kozijn deur		90	Aluminium	Hergebruik	Gemiddeld	0	0	6		1.744	2.645
	Deur		91	Hout	Hergebruik	Goed	+	+	6		1.675	2.130
	Systeemwand		95	Kunststof	Hergebruik	Gemiddeld	0	0	2		6.194	2.635
	Kozijn deur		96	Staal	Hergebruik	Gemiddeld	0	0	6		1.504	2.385
	Deur		97	Hout	Hergebruik	Goed	+	+	6		1.375	2.655
	Systeemwand		98	Glas	Hergebruik	Goed	-	-	2		4.449	2.525
	Binnenwand entrée		100	Hout en glas	Hergebruik	Goed	-	-	2		4.804	2.595
	Deur binnenwand entrée		101	Hout en glas	Hergebruik	Goed	+	+	1		1.867	2.537
	Deur meterkast		102	HPL	Hergebruik	Gemiddeld	+	+	1		3.116	2.168
	Schuifdeur entrée	Breedte schuifdeur b = 1520	103	Glas	Hergebruik	Goed	-	-	2		4.930	2.544
	Kozijn deur		106	Hout	Hergebruik	Goed	+	0	1		2.715	2.166
	Deur		107	Hout en glas	Hergebruik	Goed	+	0	1		1.865	2.100
Vloerafbouw/ vloerafwerking												
37	Vloerafwerkingen											
	Marmoleum	begane grond, 1e verd., 2e verd., 3e verd. (deels).			Recyclen	Laag	-	-	n.t.b.			
	Tapijt	overige			Recyclen	Laag	-	-	n.t.b.			
	Tegelvloer	tpv trappenhuizen, toiletten			Hergebruik	Gemiddeld	-	-	n.t.b.			
Trappen en hellingbanen												
24	Trappen en hellingconstructies											
	Trapleuning	2 per verdieping	21		Hergebruik	Goed	+	-	7			
	Trapleuning		62		Hergebruik	Goed	+	-	7			
34	Balustrades en leuningen											
	Balustrade vide	Hoogte = 1000	87	Staal	Hergebruik	Goed	-	-	1			
	Balustrade dakterras	Hoogte = 720	94	Staal	Hergebruik	Goed	-	-	+/- 10 m1			
44	Trap- en hellingafwerkingen											
	Wenteltrap	Staal	53	Staal	Hergebruik	Goed	+	-	1			
Plafonds												
45	Plafondafwerkingen											
	Plafond raster	Rasterprofielen (per verdieping)	13	Staal	Hergebruik	Gemiddeld	+	0	1800 m2	600	600	
	Systeemplafond	Stalen roosters	64	Staal	Hergebruik	Gemiddeld	+	0	30 m2	600	600	
Installaties												
Wtb.: vloeistof- en gasinstallaties												
53	Water											
	Brandslanghaspel		9		Hergebruik	Goed	+	+	28			
	Signalering brandslanghaspel		10		Hergebruik	Goed	+	+	28			

Wtb.: klimaatinstallaties												
55	Klimaatinstallatie: koeling											
	Airco unit		44		Hergebruik	Gemiddeld	+	0	+/- 5			
56	Klimaatinstallatie: verwarming											
	CV ketel	Bouwjaar omstreeks 2010	43		Hergebruik	Gemiddeld	+	+	1			
	CV ketel	Ketel 1 buiten gebruik, bouwjaar 1990	108		Recyclen	Laag	-	-	2			
	CV ketel	Bouwjaar 2005	109		Recyclen	Gemiddeld	+	-	2			
	CV ketel	tbv beg. Grond KLPD, bouwjaar 2005	110		Recyclen	Gemiddeld	-	-	1			
	CV ketel	tbv beg. Grond + 1e verd. bouwjaar 1990	111		Recyclen	Laag	-	-	1			
	Circulatiepomp	Recent vervangen	112		Hergebruik	Goed	+	+	1			
	Radiator	Ter plaatse van de kantoren	113		Recyclen	Gemiddeld	+	0	n.t.b.			
	Plaat radiator	Ter plaatse van de trappenhuizen	114		Hergebruik	Gemiddeld	+	0	n.t.b.			
57	Klimaatinstallatie: luchtbehandeling											
	Ventilatierooster		7		Hergebruik	Goed	+	+	6	600	600	
	Ventilatierooster	2 roosters per kantoorruimte, circa 150 kantoren	32		Hergebruik	Gemiddeld	+	+	150	600	600	
	Ventilatiekoker parkeerkelder		61		Hergebruik	Gemiddeld	+	+	2			
	Ventilatierooster	2 roosters per kantoorruimte, circa 150 kantoren	76		Hergebruik	Gemiddeld	+	+	150	295	295	
	Luchtbehandelingskast	Bouwjaar 1991			Recyclen	Gemiddeld	0	-				
	Luchtbehandelingskast	Bouwjaar onbekend (schatting 1995)			Recyclen	Gemiddeld	0	-				
Wtb.: energievoorziening, verlichting												
61	Centrale elektronische voorzieningen											
	Bewegingssensor		48		Hergebruik	Goed	+	+	35			
	Rooster		49		Hergebruik	Gemiddeld	+	0	n.t.b.	600	600	
63	Verlichting											
	Noodverlichting		5		Hergebruik	Goed	+	+	56			
	Noodverlichting		12		Hergebruik	Gemiddeld	+	+	56			
	Verlichting	Spaarlamp	37		Hergebruik	Gemiddeld	+	0	14			
	TL armatuur	4 tot 8 per kantoor, circa 150 kantoren	38		Hergebruik	Goed	+	-	900	1.500	300	
	TL armatuur	4 tot 8 per kantoor, circa 150 kantoren	39		Hergebruik	Goed	+	-	900	600	600	
	TL armatuur	4 tot 8 per kantoor, circa 150 kantoren	40		Hergebruik	Goed	+	-	900	1.200	300	
	Wandlamp	Spaarlamp	63						14			
Elektra: communicatie, beveiliging												
65	Beveiliging											
	Rooksensor		6		Hergebruik	Goed	+	+	56			
	Brandalarm hoorn		8		Hergebruik	Goed	+	+	56			
	Breekglas brandmelder		11		Hergebruik	Goed	+	+	56			
	Brandblusser		18		Hergebruik	Goed	+	+	42			
	Brandslangkast	Inbouw	74		Hergebruik	Goed	0	+	n.t.b.	790	790	
	Breekglas brandmelder		75		Hergebruik	Goed	+	+	n.t.b.			
Transportinstallaties												
66	Liften, roltrappen, transportbanen, transportbuizen											
	Lift	Bouwjaar 1990	22		Recyclen	Laag	-	-	1			
	Lift	Grote lift, bouwjaar 2011	84		Hergebruik	Goed	-	-	1			
	Lift	Lift, bouwjaar 2010	85		Hergebruik	Goed	-	-	1			
Vaste inrichtingen en voorzieningen												
Vaste inrichtingen en voorzieningen												
71	Vaste verkeersvoorziening											
	Stalen hekwerk parkeerkelder		60	Staal	Hergebruik	Goed	+	+	+/- 20 m1			
72	Vaste gebruikersvoorziening											
	Zonwering		4	Metaal	Hergebruik	gemiddeld	+	+	?		1.225	1.700
	Zonwering		93		Hergebruik	Goed	+	-	40		1.298	3.299
73	Vaste keukenvoorzieningen											
	Keuken		92		Hergebruik	gemiddeld	0	0	1			
74	Vaste sanitair voorzieningen											
	Toiltetpot	Diverse typen	23		Hergebruik	Gemiddeld	+	+	32			
	Toiltetbril	Diverse typen	24		Hergebruik	Gemiddeld	+	+	32			
	Spoelbak	Diverse typen	25		Hergebruik	Gemiddeld	+	+	6			
	Closetpot	Diverse typen	26		Hergebruik	Gemiddeld	+	+	2			
	Wasbak	Diverse typen	27		Hergebruik	Gemiddeld	+	+	10			
76	Vaste opslagvoorzieningen											
	Defibirlator kluis		57		Hergebruik	Goed	+	+	+/- 2			
	Whiteboard (kast)		82		Hergebruik	Goed	+	+	+/- 15		1.510	1.200
	Evac chair		99		Hergebruik	Goed	+	+	n.t.b.			
Terrein												

Table 11.5 Example dataset structure Alba Concepts

11.5 APPENDIX E: OVERVIEW MATERIALS STANDARD ROW-HOUSE ANALYSIS

Dwelling A: Standard row-house Netherlands

Based on: Krijnen, M. (2015): *Referentiewoning EPC 0,4 Tussenwoning*

Dwelling information

General

Dimensions (NVO)	[m] NVO	[m] BVO
Width	5,10	5,40
Depth (BG / 1e)	8,92	9,70
Depth (2e)	6,40	7,18
Hight BG	2,60	2,86
Hight 1e	2,60	2,86
Hight 2e	4,64	4,90
Hight total	9,84	10,62

Volume	[m3] NVO	[m3] BVO
BG	118,28	149,81
1e	118,28	149,81
2e	84,86	110,89
Total	321,42	410,50

Reusability scale
- reusability
- possible reusability
- no reusability

Building elements: *Element*	*Dimensions [m2]*	#	Building material / product: *Type*	*Dimensions [m2]*	*Product*	Reusability: *Gradation*	*Comment*
Foundation							
Site	[m2]						
Foundation	52,38		Concrete piles	?			
			Wooden piles	?			*Dmv trekken hergebruiken?*
Floors							
Surface	[m2] NVO	[m2] BVO					
BG	45,49	52,38	Channel plate floor	45,49			*Dekvloer verwijderen*
1e	45,49	52,38	Channel plate floor	35,00			*Dekvloer verwijderen*
			Concreet (landing)	10,50			*In werk gestort met prefab scheidingswand*
2e	32,64	38,77	Channel plate floor	32,64			
Total	123,62	143,53					
Exterior walls							
BG north	[m2]	#					
Window	2,60	1	Glass + frame	2,60	1		*Product moet zelfde maat zijn*
Window (door)	0,40	1	Glass + frame	0,40	1		*Product moet zelfde maat zijn*
Door	2,40	1	Front door	2,40	1		*Product moet zelfde maat zijn*
Cavity wall facade	8,50		Clickbrick	8,50			
			Sand-lime brick	8,50			
Total	15,44						
BG south	[m2]	#					
Window	9,70	1	Glass + frame	9,70	1		*Product moet zelfde maat zijn*
Cavity wall facade	5,74		Clickbrick	5,74			
			Sand-lime brick	5,74			
Total	15,44						
BG east/west	[m2]	#					
Party wall (scheidingswand)	55,48		Prefab Concrete	55,48			*Prefab elements, otherwise downcycle*
1e north	[m2]	#					
Window	5,2	2	Glass + frame	5,20	2		*Product moet zelfde maat zijn*
Cavity wall facade	10,24		Clickbrick	10,24			
			Sand-lime brick	10,24			
Total	15,44						
1e south	[m2]	#					
Window	5,2	2	Glass + frame	5,20	2		*Product moet zelfde maat zijn*
Cavity wall facade	10,24		Clickbrick	10,24			
			Sand-lime brick	10,24			
Total	15,44						
1e east/west	[m2]	#					
Party wall (scheidingswand)	55,48		Prefab Concrete	55,48			*Prefab elements, otherwise downcycle*
Roof							
2e north	[m2]	#					
Window	1,4	1	Glass + frame	1,4	1		*Product moet zelfde maat zijn*
Cavity wall facade	31,54		Roof tiles	31,54			
Total	32,94						
2e south	[m2]	#					
Cavity wall facade	32,94		Roof tiles	32,94			
Interior walls							
BG	[m2]	#					
Wall (panels)	26,84		Prefab panels Ytong (*cellenbeton*) / Faay	19,64			*Gedeeltelijk hergebruiken (uitzagen,*
Door	7,20	3	Corridor door	7,20	3		*Product moet zelfde maat zijn*
Cavity wall panels	19,64						
Total	26,84						
1e	[m2]	#					
Wall (panels)	42,75		Prefab panels Ytong (*cellenbeton*) / Faay	33,15			*Gedeeltelijk hergebruiken (uitzagen,*
Door	9,60	4	Corridor door	9,60	4		*Product moet zelfde maat zijn*
Cavity wall panels	33,15						
Total	42,75						

Building material information

Building material (/ product)		Dimensions total [m2]	Products [#]		Construction costs (virgin): *[€/m2]*	*Overview*	*Reference*	Soortelijk gewicht [kg/m3]	
Floors									
Channel plate floor	BG	45,49		6823,8	€ 36,80	€ 1.674,11	Channel plate floor 150mm	**Beton**	2100 kg/m3
	1e	35,00			€ 38,05	€ 1.331,64	Channel plate floor 200mm		
	2e	32,64			€ 38,05	€ 1.241,95	Channel plate floor 200mm		
Exterior walls									
Prefab concrete		110,97			€ 109,80	€ 12.184,21	Prefab Beton	**Beton**	2100 kg/m3
Clickbrick		34,73			€ 110,42	€ 3.834,99	Clickbricks	**Keramiek**	1800 kg/m3
Interior walls									
Prefab panels (Ytong/Faay/other)		52,80			€ 30,50	€ 1.610,30	Faay VP 54	**Faay**	970 kg/m3
Roof									
Roof tiles		64,48			€ 48,07	€ 3.099,73	Ceramic tiles	**Keramiek**	3500 kg/m3
									38,6 kg/m2
Windows									
Glass + frame		24,50	8		€ 220,70	€ 5.407,09	Meranti (wood) window	**Glas**	2500 kg/m3
								Hout	500 kg/m3
Doors									
Front door		2,40	1		€ 595,00	€ 595,00	Bossingpaneel	**Hout**	500 kg/m3
Corridor door		16,80	7		€ 100,00	€ 700,00	Opdekdeur		
French door		0	0		€ 595,00	€ -	Stapeldorpel 1/2		
								Hout	500 kg/m3
Total		**400,61 m2**							

Table 11.6 Overview materials standard row-house analysis (own table)

alba

Dwelling B: Semidetached house Netherlands
Based on: Krijnen, M. (2015): *Referentiewoning EPC 0,4 Twee-onder-eenkapwoning*

Dwelling information

General

Dimensions (NVO)	[m] NVO	[m] BVO
Width (dwelling)	5,80	6,36
Width (BG garage hallway)	1,99	2,57
Width (BG garage)	2,87	3,18
Depth (BG dwelling)	9,02	9,79
Depth (BG garage hallway)	2,13	2,57
Depth (BG garage)	5,30	5,61
Depth (1e)	9,02	9,79
Depth (2e)	6,40	7,18
Hight BG	2,60	2,86
Hight 1e	2,60	2,86
Hight 2e	4,64	4,90
Hight total	9,84	10,62

Volume	[m3] NVO	[m3] BVO
BG	186,60	247,93
1e	136,02	178,13
2e	172,24	223,76
Total	494,86	649,82

Reusability scale	
	reusability
	possible reusability
	no reusability

Building elements			Building material / product			Reusability	
Element	*Dimensions [m2]*		*Type*	*Dimensions [m2]*	*Product*	*Gradation*	*Comment*
Foundation							
Site	[m2]						
Foundation	86,69		Concrete piles	?			
			Wooden piles	?			*Dmv trekken hergebruiken?*
Floors							
Surface	[m2] NVO	[m2] BVO					
BG	71,77	86,69	Channel plate floor	71,77			*Dekvloer verwijderen*
1e	52,32	62,28	Channel plate floor	37,46			*Dekvloer verwijderen*
			Concreet (landing)	14,85			*In werk gestort met prefab scheidingswand*
2e	37,12	45,66	Channel plate floor	37,12			
Total	161,21	194,64					
Exterior walls							
BG north	[m2]	#					
Window	1,50	1	Glass + frame	1,50	1		*Product moet zelfde maat zijn*
Door	3,70	1	French doors	3,70	1		*Product moet zelfde maat zijn*
Garage door	5,70	1	Garage door	5,70	1		*Installatietechnisch niet haalbaar*
Cavity wall garage	3,38		Clickbrick	3,38			
			Sand-lime brick	3,38			
Cavity wall facade dwelling	12,99		Clickbrick	12,99			
			Sand-lime brick	12,99			
Total facade dwelling	18,19						
Total facade garage	9,08						
Total	27,27						
BG south	[m2]	#					
Window	3,70	1	Glass + frame	3,70	1		*Product moet zelfde maat zijn*
Door	2,40	1	French doors	2,40	1		*Product moet zelfde maat zijn*
Cavity wall facade	18,60		Clickbrick	18,60			
			Sand-lime brick	18,60			
Total	24,70						
BG west	[m2]	#					
Party wall (scheidingswand)	28,01		Prefab Concrete	28,01			*Prefab elements, otherwise downcycle*
Cavity wall facade	7,35		Clickbrick	7,35			
			Sand-lime brick	7,35			
Total	35,36						
BG east	[m2]	#					
Window	1,50	1	Glass + frame	1,50	1		*Product moet zelfde maat zijn*
Door	2,40	1	Front door	2,40	1		*Product moet zelfde maat zijn*
Cavity wall garage	16,03		Clickbrick	16,03			
			Sand-lime brick	16,03			
Cavity wall facade dwelling	43,43		Prefab Concrete	43,43			
Total facade garage	16,03						
Total facade dwelling	47,33						
Total	63,36						
1e north	[m2]	#					
Window	2,60	1	Glass + frame	2,60	1		*Product moet zelfde maat zijn*
Window	1,50	1	Glass + frame	1,50	1		*Product moet zelfde maat zijn*
Cavity wall facade	14,09		Clickbrick	14,09			
			Sand-lime brick	14,09			
Total	18,19						
1e south	[m2]	#					
Window	2,60	1	Glass + frame	2,60	1		*Product moet zelfde maat zijn*
Window	1,50	1	Glass + frame	1,50	1		*Product moet zelfde maat zijn*
Cavity wall facade	14,09		Clickbrick	14,09			
			Sand-lime brick	14,09			
Total	18,19						
1e west	[m2]	#					
Party wall (scheidingswand)	28,01		Prefab Concrete	28,01			*Prefab elements, otherwise downcycle*
1e east	[m2]	#					
Window	0,40	1	Glass + frame	0,40	1		*Product moet zelfde maat zijn*
Cavity wall facade	27,61		Prefab Concrete	27,61			
Total	28,01						
2e east	[m2]	#					
Cavity wall facade	20,93		Prefab Concrete	20,93			
Roof							
2e north	[m2]	#					
Window	1,7	1	Glass + frame	1,7	1		
Cavity wall facade	37,10		Roof tiles	37,10			
Total	38,80						
2e south	[m2]	#					
Cavity wall facade	38,80		Roof tiles	38,80			
Interior walls							
BG	[m2]	#					
Wall (panels)	33,46		Prefab panels Ytong (*cellenbeton*) / Faay	26,26			*Gedeeltelijk hergebruiken (uitzagen)*
Door	7,20	3	Corridor door	7,20	3		
Cavity wall facade	26,26						
Total	33,46						
1e	[m2]	#					
Wall (panels)	43,95		Prefab panels Ytong (*cellenbeton*) / Faay	34,35			*Gedeeltelijk hergebruiken (uitzagen)*
Door	9,60	4	Corridor door	9,60	4		
Cavity wall facade	34,35						
Total	43,95						

Building material information

Building material (/ product)				Construction costs (virgin)					Soortelijk gewicht [kg/m3]	
				Overview		*Factors*		*Reference*		
Floors		Dimensions total [m2]								
Channel plate floor	BG	71,77		€	36,80	€	2.641,13	Channel plate floor 150mm	**Beton**	2100 kg/m3
	1e	37,46		€	38,05	€	1.425,51	Channel plate floor 200mm		
	2e	37,12		€	38,05	€	1.412,42	Channel plate floor 200mm		
Exterior walls		Dimensions total [m2]								
Prefab Concrete		147,98		€	109,80	€	16.248,15	Prefab Beton	**Beton**	2100 kg/m3
Clickbrick		86,54		€	110,42	€	9.555,09	Clickbricks	**Keramiek**	1800 kg/m3
Interior walls		Dimensions total [m2]								
Prefab panels (Ytong/Faay/other)		60,61		€	30,50	€	1.848,52	Faay VP 54	**Faay**	970 kg/m3
Roof		Dimensions total [m2]								
Roof tiles		75,89		€	48,07	€	3.648,34	Ceramic tiles	**Keramiek**	3500 kg/m3
										38,6 kg/m2
Windows		Dimensions total [m2]	Products [#]							
Glass + frame		17,00	9	€	220,70	€	3.751,86	Meranti (wood) window	**Glas**	2500 kg/m3
									Hout	500 kg/m3
Doors		Dimensions total [m2]	Products [#]							
Front door		2,40	1	€	595,00	€	595,00	Bossingpaneel		
Corridor door		16,80	7	€	100,00	€	700,00	Opdekdeur	**Hout**	500 kg/m3
French door		6,10	2	€	595,00	€	1.190,00	Stapeldorpel 1/2		
									Hout	500 kg/m3
Total		**534,37 m2**								

Table 11.7 Overview materials semi-detached house analysis (own table)

alba — Dwelling C: Detached house Netherlands

Based on: Krijnen, M. (2015): *Referentiewoning EPC 0,4 Vrijstaande woning*

Dwelling information

General

Dimensions (NVO)	[m] NVO	[m] BVO
Width (BG)	6,02	6,84
Width (1e)	6,02	6,84
Width (2e)	4,48	5,30
Depth (BG)	10,22	11,00
Depth (1e)	10,22	11,00
Depth (2e)	10,22	11,00
Hight BG	2,60	2,86
Hight 1e	2,60	2,86
Hight 2e	2,86	3,12
Hight total	8,06	8,84

Volume	[m3] NVO	[m3] BVO
BG	159,96	215,19
1e	159,96	215,19
2e	175,96	234,75
Total	495,89	665,12

Reusability scale

- reusability
- possible reusability
- no reusability

Building elements: Element	Dimensions [m2]		Building material / product: Type	Dimensions [m2]	Product	Reusability: Gradation	Comment
Foundation							
Site	**[m2]**						
Foundation	75,24		Concrete piles	?			
			Wooden piles	?			*Dmv trekken hergebruiken?*
Floors							
Surface	**[m2] NVO**	**[m2] BVO**					
BG	61,52	75,24	Channel plate floor	61,52			*Dekvloer verwijderen*
1e	61,52	75,24	Channel plate floor	46,67			*Dekvloer verwijderen*
			Concreet (landing)	14,85			*In werk gestort met prefab scheidingswand*
2e	61,52	75,24	Channel plate floor	61,52			
Total	184,57	225,72					
Exterior walls							
BG north	**[m2]**	**#**					
Window	4,50	3	Glass + frame	4,50	3		*Product moet zelfde maat zijn*
Cavity wall facade	26,96		Clickbrick	26,96			
			Sand-lime brick	26,96			
Total	31,46						
BG south	**[m2]**	**#**					
Window	4,50	3	Glass + frame	4,50	3		*Product moet zelfde maat zijn*
Window (door)	1,10	1	Glass + frame	1,10	1		*Product moet zelfde maat zijn*
Door	2,40	1	Front door	2,40	1		*Product moet zelfde maat zijn*
Cavity wall facade	23,46		Clickbrick	23,46			
			Sand-lime brick	23,46			
Total	31,46						
BG west	**[m2]**	**#**					
Window	3,00	2	Glass + frame	3,00	2		*Product moet zelfde maat zijn*
Prefab concrete	16,56		Prefab Concrete	16,56			
Total	19,56						
BG east	**[m2]**	**#**					
Window	9,12	1	Glass + frame	9,12	1		*Product moet zelfde maat zijn*
Prefab concrete	10,44		Prefab Concrete	10,44			
Total	19,56						
1e north	**[m2]**	**#**					
Window	0,40	1	Glass + frame	0,40	1		*Product moet zelfde maat zijn*
Window	1,50	1	Glass + frame	1,50	1		*Product moet zelfde maat zijn*
Cavity wall facade	29,56		Clickbrick	29,56			
			Sand-lime brick	29,56			
Total	31,46						
1e south	**[m2]**	**#**					
Window	6,00	4	Glass + frame	6,00	4		*Product moet zelfde maat zijn*
Cavity wall facade	25,46		Clickbrick	25,46			
			Sand-lime brick	25,46			
Total	31,46						
1e west	**[m2]**	**#**					
Window	3,00	2	Glass + frame	3,00	2		*Product moet zelfde maat zijn*
Prefab concrete	16,56		Prefab Concrete	16,56			
Total	19,56						
1e east	**[m2]**	**#**					
Window	3,00	2	Glass + frame	3,00	2		*Product moet zelfde maat zijn*
Prefab concrete	16,56		Prefab Concrete	16,56			
Total	19,56						
2e west	**[m2]**	**#**					
Window	1,50	1	Glass + frame	1,50	1		
Prefab concrete	9,17		Prefab Concrete	9,17			
Total	10,67						
2e east	**[m2]**	**#**					
Window	1,50	1	Glass + frame	1,50	1		
Prefab concrete	9,17		Prefab Concrete	9,17			
Total	10,67						
Roof							
2e north	**[m2]**	**#**					
Window	1,68	1	Glass + frame	1,68	1		
Window	0,79	1	Glass + frame	0,79	1		
Cavity wall facade	43,42		Roof tiles	43,42			
Total	45,10						
2e south	**[m2]**	**#**					
Cavity wall facade	45,10		Roof tiles	45,10			
Interior walls							
BG	**[m2]**	**#**					
Wall (panels)	39,84		Prefab panels Ytong (*cellenbeton*) / Faay	32,64			*Gedeeltelijk hergebruiken (uitzagen)*
Door	7,20	3	Corridor door	7,20	3		
Cavity wall facade	32,64						
Total	39,84						
1e	**[m2]**	**#**					
Wall (panels)	55,26		Prefab panels Ytong (*cellenbeton*) / Faay	43,26			*Gedeeltelijk hergebruiken (uitzagen)*
Door	12,00	5	Corridor door	12,00	5		
Cavity wall facade	43,26						
Total	55,26						
2e	**[m2]**	**#**					
Wall (panels)	12,78		Prefab panels Ytong (*cellenbeton*) / Faay	10,38			*Gedeeltelijk hergebruiken (uitzagen)*
Door	2,40	1	Corridor door	2,40	1		
Cavity wall facade	10,38						
Total	12,78						

Building material information

Building material (/ product)		Dimensions total [m2]	Products [#]	Construction costs (virgin): Overview	Factors	Reference	Soortelijk gewicht [kg/m3]	
Floors		**Dimensions total [m2]**						
Channel plate floor	BG	61,52		€ 36,80	€ 2.264,10	Channel plate floor 150mm	**Beton**	2100 kg/m3
	1e	46,67		€ 38,05	€ 1.775,88	Channel plate floor 200mm		
	2e	61,52		€ 38,05	€ 2.341,00	Channel plate floor 200mm		
Exterior walls		**Dimensions total [m2]**						
Prefab concrete		78,47		€ 109,80	€ 8.615,99	Prefab Beton	**Beton**	2100 kg/m3
Clickbrick		105,44		€ 110,42	€ 11.642,33	Clickbricks	**Keramiek**	1800 kg/m3
Interior walls		**Dimensions total [m2]**						
Prefab panels (Ytong/Faay/other)		86,28		€ 30,50	€ 2.631,43	Faay VP 54	**Faay**	970 kg/m3
Roof		**Dimensions total [m2]**						
Roof tiles		88,52		€ 48,07	€ 4.255,40	Ceramic tiles	**Keramiek**	3500 kg/m3 38,6 kg/m2
Windows		**Dimensions total [m2]**	**Products [#]**					
Glass + frame		41,59	24	€ 220,70	€ 9.178,81	Meranti (wood) window	**Glas** **Hout**	2500 kg/m3 500 kg/m3
Doors		**Dimensions total [m2]**	**Products [#]**					
Front door		2,40	1	€ 595,00	€ 595,00	Bossingpaneel	**Hout**	500 kg/m3
Corridor door		21,60	9	€ 100,00	€ 900,00	Opdekdeur		
French door		0,00	0	€ 595,00	€ -	Stapeldorpel 1/2	**Hout**	500 kg/m3
Total		**570,02 m2**						

Table 11.8 Overview materials detached house analysis (own table)

11.8 APPENDIX H: DISASSEMBLY FACTOR WEIGHTS AND ATTRIBUTE WEIGHTS

c	Factor weight	Attribute	Score
Accessibility to connection	1.0	Accessible	1.0
		Accessible with an additional operation which causes no damage	0.8
		Accessible with an additional operation which is reparable damage	0.6
		Accessible with an additional operation which causes 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 standardized 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

Table 11.9 Disassembly factor weights and attribute weights adopted from Durmisevic (2006) (van Vliet, 2018)

Construction costs
Virgin building materials

Opmerking: In de vergelijking tussen de kosten zullen puur gegeven worden naar de assumptie van de kosten voor de bouwmaterialen. De constructiekosten (incl montage benodigdheden en manuren) zullen voor zowel virgin als reuse vergelijkbaar zijn en daarom niet meegenomen in de berekening.

Material	Type	Thickness [mm] (Specifications)	Specs (Specifications)	€ / m2	Reference	Comments	Explanation	Life cycle [years]	Reference
Floors									
	285mm thick (smallest)	285		€87 - €90					
	300mm thick	300		€90 - €93	https://www.offerteadviseur.nl/categorie/bouw/verbouwing/kosten-breedplaatvloer/	Thorough estimation of total costs / m2.			
	320mm thick	320		€93 - €96					
	340mm thick (largest)	340		€96 - €99					
	200mm thick	200	<5m span	€ 41,34					
	200mm thick	200	5m - 7,5m span	€ 43,75	http://kingspan.wis-studio3.wis.nl/Media/download/11180/Artikel_Bouwinformatie_verdiepingsvloeren.pdf	Only direct costs, no man hours or adjoining costs included.			
	260mm thick	260	<7,5m span	€ 48,84					
	260mm thick	260	5m - 7,5m span	€ 51,39					
Channel plate floor	Woningbouw	150	Max span: 4,8m	€ 36,80			BG, based on SBR 101.0.1.02	75	https://www.nibe.info/nl/members#product-6802-102-28
		150	Max span: 5,7m	€ 36,80					
		200	Max span: 6,8m	€ 38,05	http://www.bouwkosten.nl/Materiaalprijzen/Bouw,_installatie,_terrein/Systeemvloer,_kanaalplaatvloer/kostengegevens-Prijzen,_Normen_en_Tarieven/2352278.htm		1e / 2e, based on SBR 101.0.1.02	75	https://www.nibe.info/nl/members#product-6802-102-28
		200	Max span: 7,2m	€ 39,40					
		200	Max span: 8,1m	€ 40,55					
		260	Max span: 7,2m	€ 43,10					
		260	Max span: 8,1m	€ 44,45					
		260	Max span: 9,6m	€ 45,75					
Exterior walls									
Prefab Beton	Binnenspouwblad	100	Prefab beton 100 mm	€ 109,80	http://www.bouwkosten.nl/Proefabonnement_Ramen/Utiliteitsbouw/Kostenkengetallen_21_Buitenwanden,_steen/kostengegevens-Kostenkengetallen/3966000.htm		Based on tab *Recept Prefab Beton*	75	https://www.nibe.info/nl/members#product-6094-268-27
	CS12 - E100	100	.. X 538 / 648 X 997	€ 24,60					
	CS12 - E120	120	.. X 538 / 648 X 997	€ 23,25					
	CS12 - E150	150	.. X 538 / 648 X 997	€ 30,95					
	CS12 - E214	214	.. X 538 / 648 X 997	€ 42,70					
	CS12 - E240	240	.. X 538 / 648 X 997	€ 43,60					
	CS12 - E300	300	.. X 538 / 648 X 997	€ 52,85					
	CS20 - E100	100	.. X 538 / 648 X 997	€ 26,20	http://www.bouwkosten.nl/Materiaalprijzen/Bouw,_installatie,_terrein/Kalkzandsteen,_elementen/kostengegevens-Prijzen,_Normen_en_Tarieven/2433825.htm	CS12 / CS20 / CS36 are different gradations of compressive strength.			
	CS20 - E120	120	.. X 538 / 648 X 997	€ 25,15					
Sand-lime bricks	CS20 - E150	150	.. X 538 / 648 X 997	€ 33,30					
	CS20 - E175	175	.. X 538 / 648 X 997	€ 41,25					
	CS20 - E214	214	.. X 538 / 648 X 997	€ 47,45					
	CS20 - E240	240	.. X 538 / 648 X 997	€ 47,45					
	CS20 - E300	300	.. X 538 / 648 X 997	€ 57,50					
	CS36 - EH175	175	.. X 538 / 648 X 997	€ 49,75					
	CS36 - EH214	214	.. X 538 / 648 X 997	€ 62,55					
	CS36 - EH250	250	.. X 538 / 648 X 997	€ 63,35					
	CS36 - EH300	300	.. X 538 X 997	€ 79,50					
Clickbricks	Diverse soorten	90	240mm X 100mm	€ 110,42	http://www.bouwkosten.nl/Materiaalprijzen/Bouw,_installatie,_terrein/Baksteen,_Click_Brick/kostengegevens-Prijzen,_Normen_en_Tarieven/2355256.htm	Calculation € / m2 clickbrick*	0	75	https://www.nibe.info/nl/members#product-6025-84-106
Prefab HSB	Buitenwanden (constructief)		HSB buitenwanden en muurplaten. HBS pakket tuinkasten	€ 347,33	http://www.bouwkosten.nl/Projectanalyses/Nieuwbouw,_uitwerking/40_houtskeletbouwwoningen_te_Zwolle/kostengegevens-Projectanalyses/2347154.htm#Kostenopniveau2Elementenclusters\	Compleet panels, in comparison to clickbricks and sand-lime bricks, which lacks the complete construction of the facade.			
	Binnenwanden (constructief)		HSB woningscheidende en stabiliteitswanden	€ 276,57					
Interior walls									
	Ytong G4/600 Blok	50	600mm X 200mm	€ 14,76			8,2		
		70	600mm X 200mm	€ 18,37		8,2 blocks / m2, €/block.			
		100	600mm X 200mm	€ 26,65	https://www.online-bouwmaterialen.nl/stenen/ytong-blokken-gasbeton-cellenbeton/				
		150	600mm X 200mm	€ 47,72					
		50	600mm X 400mm	€ 14,84			4,1		
		70	600mm X 400mm	€ 18,12		4,1 blocks / m2, €/block.			
		100	600mm X 400mm	€ 26,08					
Prefab Panels		100	600mm X 250mm	€ 29,77		6,6 blocks / m2, €/block.	6,6		
	Faay VP 54	57	2400mm X 400mm	€ 30,50	https://www.sleiderink.nl/faay-vp54?child_id=11598&quantity=1&gclid=CjwKCAjwkenqBRBgEiwA-bZVto1eTogQ9vJ1YJU77mHXRPN6O8grl0fgx6EH7rolb8ioTvdONkxWIxoCNB0QAvD_BwE	Maat verschil in afname panelen	Bsaed on price certainty	60	https://www.nibe.info/nl/members#product-6832-93-27
		57	2600mm X 400mm	€ 30,50					
		57	2800mm X 400mm	€ 30,50					
		57	3000mm X 400mm	€ 30,50					
		57	3200mm X 400mm	€ 30,50					
		57	3600mm X 400mm	€ 30,50					
Roof									
	Concrete tiles		Life cycle 30 years	€ 50,00	https://www.dakdekker-weetjes.nl/dakbedekking/dakpannen/				
	Ceramic tiles		Life cycle 50 years	€ 60,00					
Roof tiles	Concrete tiles			€ 56,75	http://www.bouwkosten.nl/Proefabonnement_Ramen/Utiliteitsbouw/Kostenkengetallen_47_Dakafwerkingen/kostengegevens-Kostenkengetallen/3966003.htm				
	Ceramic tiles	20	Totaal	€ 48,07			Based on SBR 401.0.3.01.T1	75	https://www.nibe.info/nl/members#product-6873-113-105
			Totaal (incl. manuren)	€ 73,65					
Windows									
	Plastic (kunststof) window		incl. montage & HR++	€700 - €800	https://www.kozijnen-weetjes.nl/ramen/				
	Wooden window		incl. montage & HR++	€750 - €900					
	Aluminium window		incl. montage & HR++	€800 - €950					
	Glass	6							
Window	Meranti (wood) window	115	Totaal	€ 220,70	http://www.bouwkosten.nl/Proefabonnement_Ramen/Utiliteitsbouw/Kostenkengetallen_31_Buitenwandopeningen,_gevelkozijn/kostengegevens-Kostenkengetallen/3966001.htm		Based on SBR 201.0.3.01 Based on tab *Recept Meranti Kozijn*	35	https://www.nibe.info/nl/members#product-6624-269-32
			Totaal (inc. Manuren)	€ 567,00					
	Plastic (kunststof) window			€ 395,00					
	Aluminium window			€ 530,00					
	Steel window			€ 826,00					
Doors		*Specs*	*Hight*						
Corridor door	Opdekdeur	Incl. montage		€55 - €75	https://www.werkspot.nl/binnendeur-plaatsen-vervangen/prijzen-kosten				
	Opdekdeur	Incl. montage		€ 100,00			Realistic	75	https://www.nibe.info/nl/members#product-6125-136-33
	Achterdeur	No window	2115mm	€ 571,00					
			2315mm	€ 606,00					
		Stapeldorpel 1/4	2115mm	€ 526,00					
			2315mm	€ 643,00					
		Stapeldorpel 1/2	2115mm	€ 595,00			Based on drawing house	75	
			2315mm	€ 688,00					
	Voordeur	4x bossingpaneel	2115mm	€ 1.315,00					
			2315mm	€ 1.330,00					
		Verticale groeven	2115mm	€ 987,00	http://www.bouwkosten.nl/Materiaalprijzen/Bouw,_installatie,_terrein/Buitendeur,_merbau/kostengegevens-Prijzen,_Normen_en_Tarieven/4423242.htm				
Facade door			2315mm	€ 1.005,00					
		1x paneel	2115mm	€ 1.440,00					
			2315mm	€ 1.455,00					
		Bossingpaneel en tussendorpel 1/2	2115mm	€ 1.085,00					
			2315mm	€ 1.100,00					
		Bossingpaneel en tussendorpel 1/3	2115mm	€ 1.340,00					
			2315mm	€ 1.355,00					
		Bossingpaneel	2115mm	€ 809,00			Standard cheapest front door	75	
			2315mm	€ 925,00					
		4 ruits met roeden en bossingpanee	2115mm	€ 1.165,00					
			2315mm	€ 1.180,00					

	Height [mm]	Width [mm]	Surface [mm2]
Dimension clickbrick	240	100	24000
Square meter	1000	1000	1000000
Bricks / square meter	1000000	24000	41,66666667
Calculation	Costs	Pieces	
	€ 2.650,00	1000	
	€ 110,42	41,66666667	

Table 11.10 Overview costs virgin building materials (own table)

11.10 APPENDIX J: OVERVIEW DECONSTRUCTION / TRANSPORTATION COSTS REUSABLE BUILDING MATERIALS

alba

Construction costs
Reused building materials

Opmerking: In de vergelijking tussen de kosten zullen puur gegeken worden naar de assumptie van de kosten voor de bouwmaterialen. De constructiekosten (inccl montage benodigdheden en manuren) zullen voor zowal virgin als reuse vergelijkbaar zijn en daarom niet meegenomen in de berekening.

Specifications

	Sloop / demontage kosten $f_{k.1.1}$						Additionele vervoerskosten naar nieuwe locatie			
Material	*Source O $m_{k1\,[kg]}$*	*€ total*	*€ / m2*	*Source P $m_{k1\,[kg]}$*	*€ total*	*€ / m2*	*Source O*	*/ m2*	*Source P*	*/ m2*
Floors										
Channel plate floor 150mm	14329,98	€ 722,10	€ **15,87**	22607,50	€ 1.228,28	€ **17,11**	€ 26.528,91	€ **5,31**	€ 15.159,38	€ **3,79**
Channel plate floor 200mm	28407,54	€ 1.431,49	€ **21,16**	23493,96	€ 1.276,45	€ **17,11**	€ 42.446,25	€ **5,31**	€ 22.739,06	€ **3,79**
Exterior walls										
Prefab Beton	23303,28	€ 1.268,22	€ **11,43**	31075,90	€ 1.823,45	€ **12,32**	€ 33.603,28	€ **3,54**	€ 22.739,06	€ **2,53**
Clickbricks	5626,58	€ 430,97	€ **12,41**	14018,93	€ 1.157,72	€ **13,38**	€ 27.286,88	€ **2,73**	€ 15.592,50	€ **1,95**
Interior walls										
Prefab Panels	2919,14	€ 200,05	€ **3,79**	3350,97	€ 247,60	€ **4,09**	€ 7.450,33	€ **0,93**	€ 4.656,45	€ **0,67**
Roof										
Roof tiles	4513,60	€ 327,52	€ **5,08**	5312,44	€ 415,63	€ **5,48**	€ 5.895,31	€ **1,18**	€ 3.368,75	€ **0,84**
Windows										
Glass	294	€ 23,70	€ **1,21**	204	€ 17,73	€ **1,30**	€ 1.364,34	€ **0,28**	€ 812,11	€ **0,20**
Frame	281,75	€ 20,44	€ **4,17**	195,5	€ 15,30	€ **4,50**	€ 581,11	€ **0,48**	€ 345,90	€ **0,35**
Doors										
Corridor door	168	€ 12,19	€ **0,73**	168	€ 13,14	€ **0,78**	€ 84,22	€ **0,17**	€ 48,13	€ **0,12**
Facade door	24	€ 1,74	€ **0,73**	24	€ 1,88	€ **0,78**	€ 842,19	€ **0,17**	€ 481,25	€ **0,12**
								€ **20,09**		€ **14,35**

TDSK Referentiewoning 1 (source O)

M2 bvo		143,53
Gem €/m2	€	28,04
$f_{functie}$		0,8
f_{hoogte}		1
TDSK	€	3.219,71

TDSK Referentiewoning 2 (source P)

M2 bvo		194,64
Gem €/m2	€	28,04
$f_{functie}$		0,8
f_{hoogte}		1
TDSK	€	4.366,08

TDSK Referentiewoning 3 (source ?)

M2 bvo		225,72
Gem €/m2	€	28,04
$f_{functie}$		0,8
f_{hoogte}		1
TDSK	€	5.063,35

TDSK Referentiewoning 1

m_{gebouw}	79867,87 kg	
$Ll_{k.1}$	Laatste tabel	*Uitleg financieel hfd*
$i_{funct./techn.ld}$	n.v.t.	*Uitleg financieel hfd*

TDSK Referentiewoning 2

m_{gebouw}	100451,20 kg	
$Ll_{k.1}$	Laatste tabel	*Uitleg financieel hfd*
$i_{funct./techn.ld}$	n.v.t.	*Uitleg financieel hfd*

TDSK Referentiewoning 3

m_{gebouw}	99206,23 kg	
$Ll_{k.1}$	Laatste tabel	*Uitleg financieel hfd*
$i_{funct./techn.ld}$	n.v.t.	*Uitleg financieel hfd*

Referentiewoning 1 (source O)

Distance source [km]		35
Default distance Stone [km]		20
Default distance Wood [km]		50
Default distance Glass [km]		150
€/km	€	1,10
Max gewicht [kg]		4000
Gem. gewicht [kg]		3200
Inhoud [m³]		55,2
Gem. inhoud [m³]		44,16
Laden (20%)		20%
Lossen (20%)		20%

Stone

Subtotaal	€	38,50
Laden & lossen		40%
Totaal	€	53,90
Prijs per kg	€	0,017
Prijs per m³	€	1,22

Materials dwelling 1 [m2]		400,61
Costs all materials dwelling 1 [€/m2]	€	20,09
Total transport costs dw 1	€	8.049,44
Weight dwelling 1 [kg]		79867,87
Average capacity truck		3200
Total # of rides for 1 truck		**25**
	€	322,51
1 ride price per M3	€	67,38
1 ride price per KG	€	53,900

Referentiewoning 2 (source P)

Distance [km]		25
Default distance Stone [km]		20
Default distance Wood [km]		50
Default distance Glass [km]		150
€/km	€	1,10
Max gewicht [kg]		4000
Gem. gewicht [kg]		3200
Inhoud [m³]		55,2
Gem. inhoud [m³]		44,16
Laden (20%)		20%
Lossen (20%)		20%

Stone

Subtotaal	€	27,50
Laden & lossen		40%
Totaal	€	38,50
Prijs per kg	€	0,012
Prijs per m³	€	0,87

Materials dwelling 1 [m2]		534,37
Costs all materials dwelling 1 [€/m2]	€	14,35
Total transport costs dw 1	€	7.669,42
Weight dwelling 1 [kg]		100451,20
Average capacity truck		3200
Total # of rides for 1 truck		**31**
	€	244,32

Table 11.11 Overview deconstruction / transportation costs reusable building materials (own table)

11.11 APPENDIX K: OVERVIEW OF MATERIAL VALIDATION REUSABLE BUILDING MATERIALS

Construction costs
Reused building materials

Specifications
Waardering materialen factor

Virgin eur/m2	Inside / outside facade	Factor	Vertical / horizontal pressure	Factor	Lifespan material	Factor O	Factor P	€ Source O (Inside / outside)	€ Source P (Inside / outside)	€ Source O (Pressure)	€ Source P (Pressure)	Interfacing materials	Factor	Accessibility of connection	Factor	LI (Losmaakbaarheidindex)	Additional costs LI factor/m2
€ 36,80	Inside	0,8	Horizontal BG	0,7	75,0	0,4	0,3	€ 4,42	€ 5,20	€ 6,62	€ 7,80	Filled hard chemical connection	0,1	Toegankelijkheid met extra ha	0,4	0,25	€ 27,60
€ 38,05	Inside	0,8	Horizontal 1st floor	0,8	75,0	0,4	0,3	€ 4,57	€ 5,38	€ 4,57	€ 5,38	Filled hard chemical connection	0,1	Toegankelijkheid met extra ha	0,4	0,25	€ 28,54
€ 109,80	Partially inside / outside	0,7	Vertical outside 2 floors	0,9	75,0	0,4	0,3	€ 19,76	€ 23,28	€ 6,59	€ 7,76	Filled hard chemical connection	0,1	Toegankelijkheid met extra ha	0,6	0,35	€ 71,37
€ 110,42	Outside	0,6	Vertical outside 2 floors	0,8	75,0	0,4	0,3	€ 26,50	€ 31,21	€ 13,25	€ 15,61	Direct connection with additional fixing devices	0,8	Vrij toegankelijk	1,0	0,90	€ 11,04
€ 30,50	Inside	0,6	Vertical Inside 1 floor	0,9	60,0	0,5	0,4	€ 6,10	€ 7,73	€ 1,53	€ 1,93	Direct connection with additional fixing devices	0,8	Toegankelijkheid met extra ha	0,6	0,70	€ 9,15
€ 48,07	Outside	0,6	No pressure	1,0	75,0	0,4	0,3	€ 11,54	€ 13,59	€ -	€ -	Direct connection with additional fixing devices	0,8	Toegankelijkheid met extra ha	0,8	0,80	€ 9,61
€ 220,70	Outside	0,6	Vertical outside 2 floors	0,8	35,0	0,9	0,6	€ 12,61	€ 32,79	€ 6,31	€ 16,39	Dry connections (with or without accesory external	1,0	Vrij toegankelijk	1,0	1,00	
€ 220,70	Outside	0,6	Vertical outside 2 floors	0,8	35,0	0,9	0,6	€ 12,61	€ 32,79	€ 6,31	€ 16,39	Direct connection with additional fixing devices	0,8	Toegankelijkheid met extra ha	0,8	0,80	€ 44,14
€ 100,00	Inside	0,8	Vertical Inside 1 floor	0,9	75,0	0,4	0,3	€ 12,00	€ 14,13	€ 6,00	€ 7,07	Direct connection with additional fixing devices	0,8	Toegankelijkheid met extra ha	0,8	0,80	€ 20,00
€ 595,00	Outside	0,6	Vertical outside 2 floors	0,8	75,0	0,4	0,3	€ 142,80	€ 168,19	€ 71,40	€ 84,09	Direct connection with additional fixing devices	0,8	Toegankelijkheid met extra ha	0,8	0,80	€ 119,00

(based on virgin material costs, correction factor for extra costs / materials)

Inside / outside facade	Factor
Inside	0,8
Outside	0,6

Vertical / horizontal pressure	Factor
Horizontal BG	0,7
Horizontal 1st floor	0,8
Horizontal 2nd floor	0,9
Vertical outside 1 floor	0,9
Vertical outside 2 floors	0,8
Vertical Inside 1 floor	0,9
Vertical Inside 2 floors	0,8
No pressure	1,0

Lifespan	Years	Years
Source construction year	1989	1994
t [years]	30	22

Life span formula's

€Reuse = (1-(t/LSm)) * €Virg * (1-factor in/out)

€Reuse = (1-(t/LSm)) * €Virg * (1-factor pressure)

Type of connection	Factor
Dry connections (with or without accesory external connection)	1
Dry connection	1,0
Click connection	1,0
Velcro connection	1,0
Magnetic connection	1,0
Direct connection with additional fixing devices	0,8
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	0,6
Pin connection	0,6
Nail connection	0,6
Filled soft chemical connection	0,2
Putty connection	0,2
Filled hard chemical connection	0,1
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

Accessibility of connection	Factor
Vrij toegankelijk	1,0
Toegankelijkheid met extra handelingen die geen schade veroorzaken	0,8
Toegankelijkheid met extra handelingen met herstelbare schade	0,6
Toegankelijkheid met extra handelingen met herstelbare schade > 20% vd bouwkosten	0,4
Niet toegankelijk onherstelbare schade aan objecten	0,1

Table 11.12 Overview material validation reusable building materials (own table)

11.12 APPENDIX L: PROJECT-BASED MODEL INPUT

alba **Input**

Minimum and maximum amounts of dwellings per type

Dwellings	*Dwelling type*	*A: Row-house*	*B: Semi-detached house*	*C: Detached house*
	Minimum	10	20	12
	Maximum	40	50	60

Amount of building material [m2] required per material and dwelling type (A,B & C)

	Dwelling type	*A: Row-house*	*B: Semi-detached house*	*C: Detached house*
Floors	Channel plate floor BG	45,49	71,77	61,52
	Channel plate floor 1e / 2e	67,64	74,58	108,20
	Total	113,13	146,35	169,72
Exterior wall	Prefab concrete	110,97	147,98	78,47
	Clickbrick	34,73	86,54	105,44
	Total	145,70	234,52	183,91
Interior wall	Panels (Ytong/Faay/other)	52,80	60,61	86,28
Roof	Roof tiles	64,48	75,89	88,52
Windows	Glass + frame	24,50	17,00	41,59
Doors [#]	Front door	1,00	1,00	1,00
	Corridor door	7,00	7,00	9,00
	French door	0,00	2,00	0,00
	Total	8,00	10,00	10,00
	Total	*400,61*	*534,37*	*570,02*

Amounts of material available per type and source *(hypothetical)*

		Source O	*Source P*
Floors	Channel plate floor BG	5.000	4.000
	Channel plate floor 1e / 2e	8.000	6.000
Exterior wall	Prefab concrete	9.500	9.000
	Clickbrick	10.000	8.000
Interior wall	Panels (Ytong/Faay/other)	8.000	7.000
Roof	Roof tiles	5.000	4.000
Windows	Glass + frame	6.000	5.000
Doors [#]	Front door	500	400
	Corridor door	5.000	4.000
	French door	600	500

Geographical data *(hypothetical)*

	Source O	*Source P*
Distance [km]	60	30

Costs 'Reused' building materials

		Source O	*Source P*
Floors	Channel plate floor BG	€ 63,61	€ 62,26
	Channel plate floor 1e / 2e	€ 67,93	€ 60,95
Exterior wall	Prefab concrete	€ 115,21	€ 117,76
	Clickbrick	€ 67,88	€ 73,58
Interior wall	Panels (Ytong/Faay/other)	€ 22,16	€ 23,69
Roof	Roof tiles	€ 28,25	€ 29,69
Windows	Glass + frame	€ 88,67	€ 148,97
Doors [#]	Front door	€ 334,21	€ 372,21
	Corridor door	€ 39,01	€ 42,13
	French door	€ 334,21	€ 372,21

Budget

	€ 5.000.000,00

Costs 'Virgin 'building materials

		[eur/m2]
Floors	Channel plate floor BG	€ 36,80
	Channel plate floor 1e / 2e	€ 38,05
Exterior wall	Prefab concrete	€ 109,80
	Clickbrick	€ 110,42
Interior wall	Panels (Ytong/Faay/other)	€ 30,50
Roof	Roof tiles	€ 48,07
Windows	Glass + frame	€ 220,70
Doors [#]	Front door	€ 595,00
	Corridor door	€ 100,00
	French door	€ 595,00

Costs per dwelling type (Virgin materials)

	Material	*A: Row-house*	*B: Semi-detached house*	*C: Detached house*
Floors	Channel plate floor BG	€ 1.674	€ 2.641	€ 2.264
	Channel plate floor 1e / 2e	€ 2.574	€ 2.838	€ 4.117
Exterior wall	Prefab concrete	€ 12.184	€ 16.248	€ 8.616
	Clickbrick	€ 3.835	€ 9.555	€ 11.642
Interior wall	Panels (Ytong/Faay/other)	€ 1.610	€ 1.849	€ 2.631
Roof	Roof tiles	€ 3.100	€ 3.648	€ 4.255
Windows	Glass + frame	€ 5.407	€ 3.752	€ 9.179
Doors [#]	Front door	€ 595	€ 595	€ 595
	Corridor door	€ 700	€ 700	€ 900
	French door	€ -	€ 1.190	€ -
	Total	**€ 31.679**	**€ 43.016**	**€ 44.200**

Table 11.13 Input page project-based model (own table)

Input

	Dwelling type A	Dwelling type B	Dwelling type C
Minimum amount of dwellings	10	20	12
Maximum amount of dwellings	40	50	60

Budget	€ 5.000.000,00

Sources	Source O	Source P	
Distance [km]	60	30	*(hypothetical)*

Construction year	Source O [1989]	Source P [1997]	
t [years]	30	22	*(hypothetical)*

	Amounts of material available per type and source [m2]	Source O	Source P	
Floors	Channel plate floor BG	5.000	4.000	*(hypothetical)*
	Channel plate floor 1e / 2e	8.000	6.000	
Exterior wall	Prefab concrete	9.500	9.000	
	Clickbrick	10.000	8.000	
Interior wall	Panels (Ytong/Faay/other)	8.000	7.000	
Roof	Roof tiles	5.000	4.000	
Windows	Glass + frame	6.000	5.000	
Doors [#]	Front door	500	400	
	Corridor door	5.000	4.000	
	French door	600	500	

Table 11.14 Solve page input Project-based model (own table)

11.13 APPENDIX M: PROJECT-BASED MODEL OUTPUT

Output

Dwelling type configuration

	Dwelling type	A: Row-house	B: Semi-detached house	C: Detached house
Dwellings	Optimal	10	50	52

Amounts of material used per type and dwelling type

	Dwelling type	A: Row-house	B: Semi-detached house	C: Detached house
Floors	Channel plate floor BG	455	3.588	3.170
	Channel plate floor 1e / 2e	676	3.729	5.574
Exterior wall	Prefab concrete	1.110	7.399	4.043
	Clickbrick	347	4.327	5.432
Interior wall	Panels (Ytong/Faay/other)	528	3.030	4.445
Roof	Roof tiles	645	3.795	4.561
Windows	Glass + frame	245	850	2.143
Doors [#]	Front door	10	50	52
	Corridor door	70	350	464
	French door	0	100	0

Amounts of Reused building material used per type and source

	Used	Source O	Source P
Floors	Channel plate floor BG	3.213	4.000
	Channel plate floor 1e / 2e	3.980	6.000
Exterior wall	Prefab concrete	9.500	3.052
	Clickbrick	10.000	106
Interior wall	Panels (Ytong/Faay/other)	8.000	3
Roof	Roof tiles	5.000	4.000
Windows	Glass + frame	3.238	0
Doors [#]	Front door	112	0
	Corridor door	884	0
	French door	100	0

Costs 'Reused' building materials

	Used	Source O	Source P	Total
Floors	Channel plate floor BG	€ 204.387	€ 249.059	€ 453.446
	Channel plate floor 1e / 2e	€ 270.354	€ 365.730	€ 636.084
Exterior wall	Prefab concrete	€ 1.094.532	€ 359.350	€ 1.453.882
	Clickbrick	€ 678.777	€ 7.834	€ 686.612
Interior wall	Panels (Ytong/Faay/other)	€ 177.285	€ 79	€ 177.364
Roof	Roof tiles	€ 141.263	€ 118.761	€ 260.025
Windows	Glass + frame	€ 287.099	€ -	€ 287.099
Doors [#]	Front door	€ 37.272	€ -	€ 37.272
	Corridor door	€ 34.476	€ -	€ 34.476
	French door	€ 33.421	€ -	€ 33.421

Costs 'Virgin' building materials

	Used	Total
Floors	Channel plate floor BG	€ 265.445
	Channel plate floor 1e / 2e	€ 379.736
Exterior wall	Prefab concrete	€ 1.378.151
	Clickbrick	€ 1.115.924
Interior wall	Panels (Ytong/Faay/other)	€ 244.102
Roof	Roof tiles	€ 432.655
Windows	Glass + frame	€ 714.561
Doors [#]	Front door	€ 66.355
	Corridor door	€ 88.369
	French door	€ 59.500

Comparison costs between reused / virgin building materials

		Re-use	Virgin
Floors	Channel plate floor BG	€ 453.446	€ 265.445
	Channel plate floor 1e / 2e	€ 636.084	€ 379.736
Exterior wall	Prefab concrete	€ 1.453.882	€ 1.378.151
	Clickbrick	€ 686.612	€ 1.115.924
Interior wall	Panels (Ytong/Faay/other)	€ 177.364	€ 244.102
Roof	Roof tiles	€ 260.025	€ 432.655
Windows	Glass + frame	€ 287.099	€ 714.561
Doors [#]	Front door	€ 37.272	€ 66.355
	Corridor door	€ 34.476	€ 88.369
	French door	€ 33.421	€ 59.500
	Total	**€ 4.059.681**	**€ 4.744.797**

Comparison costs between reused / virgin building materials (/ m2) (source O)

		Re-use	Virgin
Floors	Channel plate floor BG	€ 63,61	€ 36,80
	Channel plate floor 1e / 2e	€ 67,93	€ 38,05
Exterior wall	Prefab concrete	€ 115,21	€ 109,80
	Clickbrick	€ 67,88	€ 110,42
Interior wall	Panels (Ytong/Faay/other)	€ 22,16	€ 30,50
Roof	Roof tiles	€ 28,25	€ 48,07
Windows	Glass + frame	€ 88,67	€ 220,70
Doors [#]	Front door	€ 334,21	€ 595,00
	Corridor door	€ 39,01	€ 100,00
	French door	€ 334,21	€ 595,00

Comparison costs between reused / virgin building materials (/ m2) (source P)

		Re-use	Virgin
Floors	Channel plate floor BG	€ 62,26	€ 36,80
	Channel plate floor 1e / 2e	€ 60,95	€ 38,05
Exterior wall	Prefab concrete	€ 117,76	€ 109,80
	Clickbrick	€ 73,58	€ 110,42
Interior wall	Panels (Ytong/Faay/other)	€ 23,69	€ 30,50
Roof	Roof tiles	€ 29,69	€ 48,07
Windows	Glass + frame	€ 148,97	€ 220,70
Doors [#]	Front door	€ 372,21	€ 595,00
	Corridor door	€ 42,13	€ 100,00
	French door	€ 372,21	€ 595,00

Table 11.15 Project-based model output (own table)

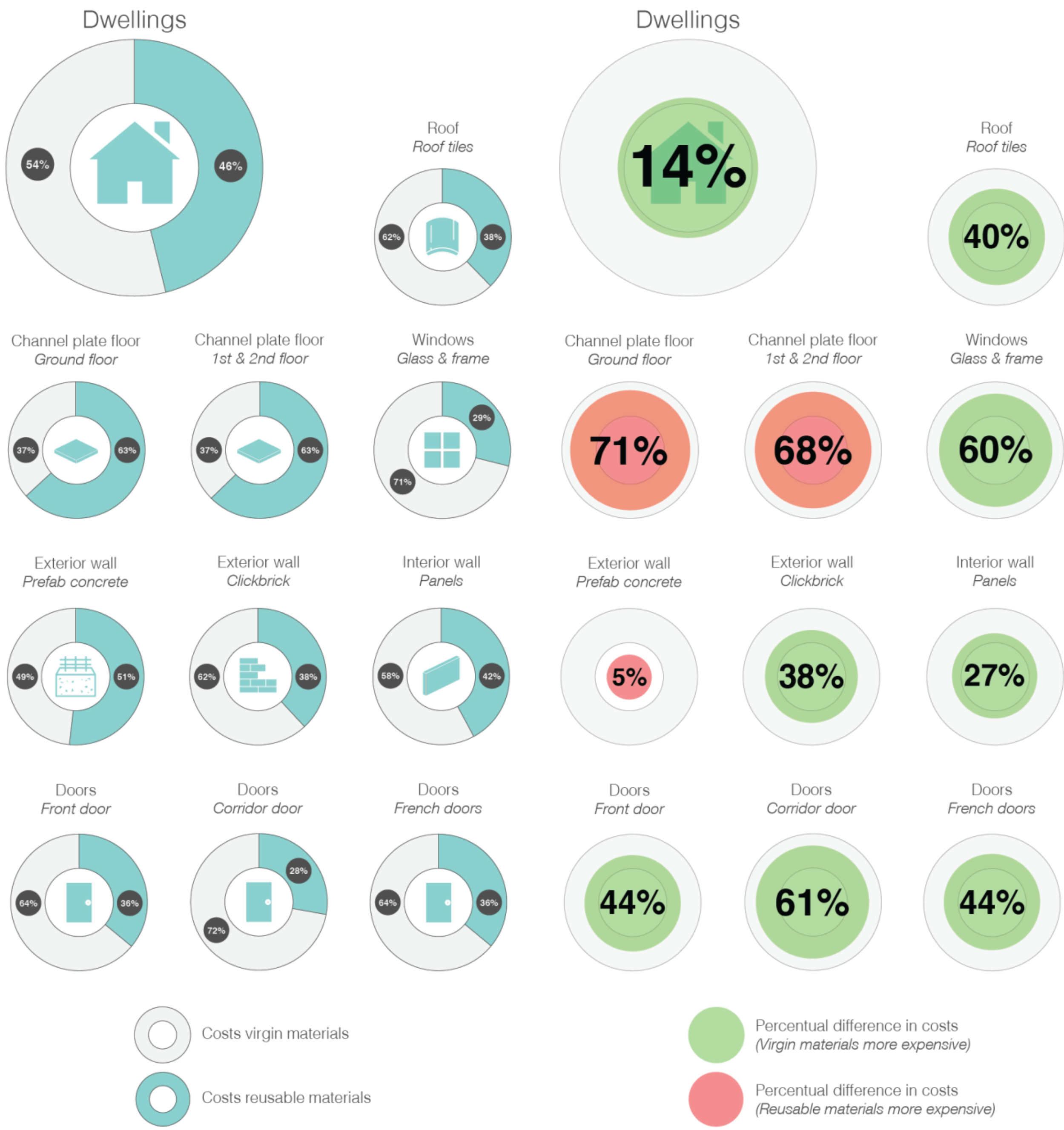
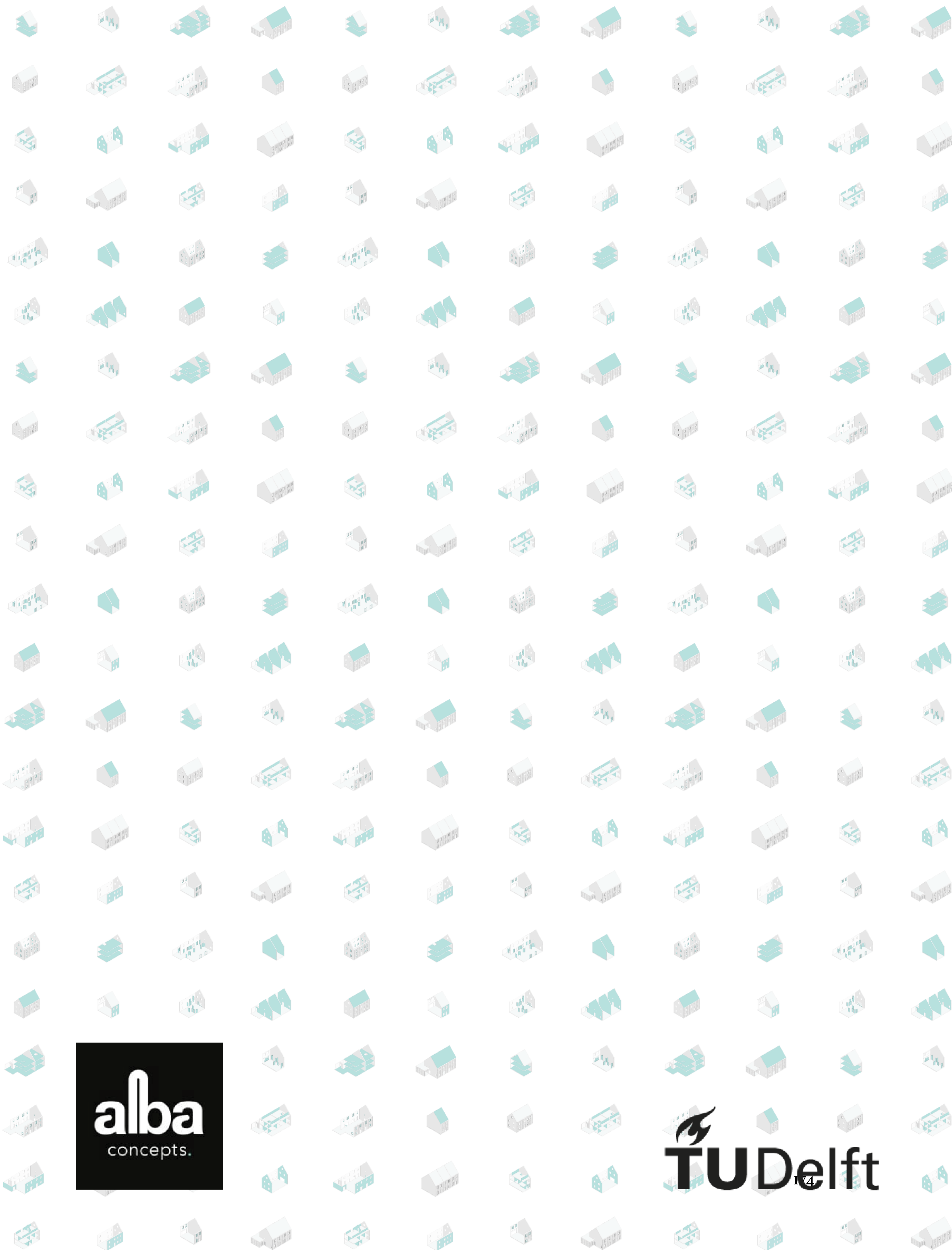


Table 11.16 Project-based model output Solve tab (own table)



alba concepts.

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