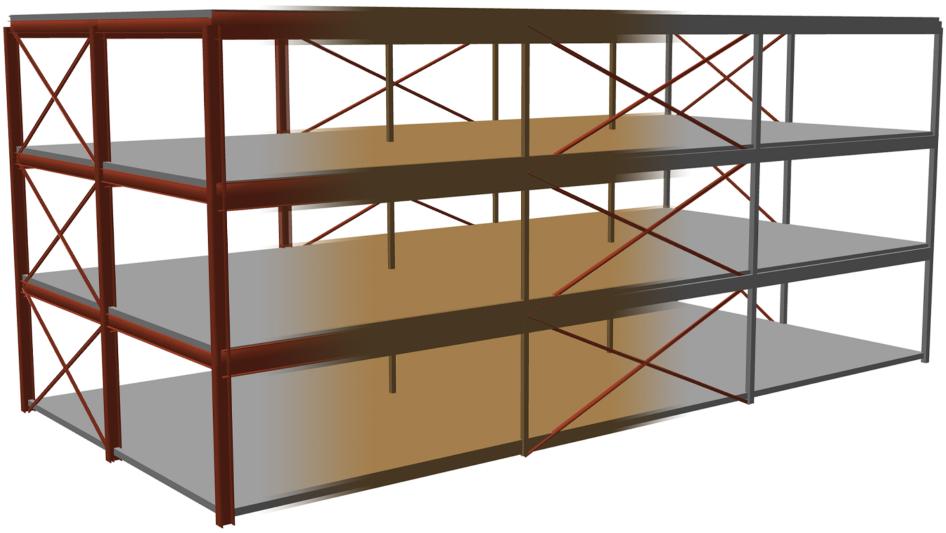
MSc. Thesis report

STRUCTURAL SUSTAINABILITY IN THE EARLY DESIGN PHASE

A parametric environmental impact assessment of various construction materials, including the design for deconstruction and donor structural framework concepts



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STRUCTURAL SUSTAINABILITY IN THE EARLY DESIGN PHASE

A parametric environmental impact assessment of various construction materials, including the design for deconstruction and donor structural framework concepts

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science in Structural Engineering, Structural Mechanics

by

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Structural sustainability in the early design phase (2020)

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SUMMARY

The Netherlands is currently in the process of transitioning from a linear economy to a circular economy, in accordance with the "Nederland Circulair 2050" policy. To increase the circularity of buildings, several approaches can be integrated. In this research, the so–called Design for Deconstruction and Donor Structural Framework concepts are elaborated as possible approaches. The first concept focuses on taking the future de– and remountability of a building into consideration during the design process. This concept allows buildings that approach their end–of–life phase to be (partially) reused as structural components, on a new location. The second concept can be applied during the construction phase of a building, where structural components of an old building are dismantled and reused in the to be constructed building. The difference between the two concepts thus being the life cycle in which they are applied. Therefore, the resulting benefit of using a Donor Framework can be seen immediately, whereas the benefit of applying the Design for Deconstruction concept can only be stated in the future.

Unfortunately, the current procedure to measure the sustainability score of a building, the Life Cycle Assessment methodology, does not take these concepts into account. This makes determining their impact on the environment hardly possible. Also, due to the fact that detailed information about a design is required, a Life Cycle Assessment is made only once the design is final. In this order, all design variables are set such that designing towards sustainability is not an option.

This research focuses on solving the introductory problems and aims to enable sustainable material choices for a structural design possible in the early design phase. Both the Donor Structural Framework and the Design for Deconstruction concepts were taken into consideration. This main goal has been split into two sub–questions:

1. How to assess the environmental impact of a steel, concrete and timber load bearing structure in the early design phase?

2. How to implement the Donor Structural Framework and the Design for Deconstruction concept into the existing Life Cycle Assessment methodology?

The research questions have been answered by executing the following approach:

1. A parametric model is used in which not only the geometry and structural calculations are included, but the Environmental Impact Calculation as well. In the event of a design change, the Environmental Impact Calculation is automatically reiterated, which means different designs can be compared quickly based on their environmental impact. The model constructed for this study is suitable for designs in steel, concrete and timber. For each material a reference design is created. The Bill of Materials of these designs serves as input for the Environmental Impact Calculation on which the materials were compared in a later research phase.

2. First, an existing end–of–life allocation method has been adjusted to include reuse during both the construction phase (Donor Structural Framework) as the end—of–-life phase (Design for Deconstruction). Secondly, the Building Circularity Index, which recognizes a "circularity score", has been implemented in this method. In this study the Building Circularity Index is assumed as the "probability of future reuse of the building". The modified method was

implemented in the parametric model to enable a real-–time Environmental Impact Calculation.

This approach has been fully implemented into a parametric visual script, executed in the Grasshopper, a parametric environment plugin of Rhino which enables visual scripting. Input parameters are imported from Excel, the Grasshopper script calculates the environmental impact and exports the results to Excel where they are visualized in a dashboard.

Ultimately, the developed parametric model has been divided into a part containing the geometry and structural calculations of the reference designs and a part where the newly developed Environmental Impact Calculation method is implemented. Combining the results of both parts in the total model, it becomes possible to assess whether a design is best built in a certain material in the early design phase. The final model can provide results with or without the use of a Donor Structural Framework and with or without application of the Design for Deconstruction concept.

For the purpose of demonstrating the functioning of the model, a reference design in steel, concrete and timber was implemented as a basic geometry. This geometry was assumed equal across all designs and for comparability purposes, dimensions were fixed.

Consequently, it can be concluded from the results of these reference designs shown in Figure 0.1, that using a Donor Structural Framework results in a lower environmental impact than applying the Design for Deconstruction concept by maximizing the remountability of a structure. Until a lifespan of 75 years, using a timber donor framework is the most sustainable solution for the reference design. From 75 until 100 years this is the case for steel and from 100 years onward, a concrete design, whether or not using a donor framework, results in the lowest environmental impact.

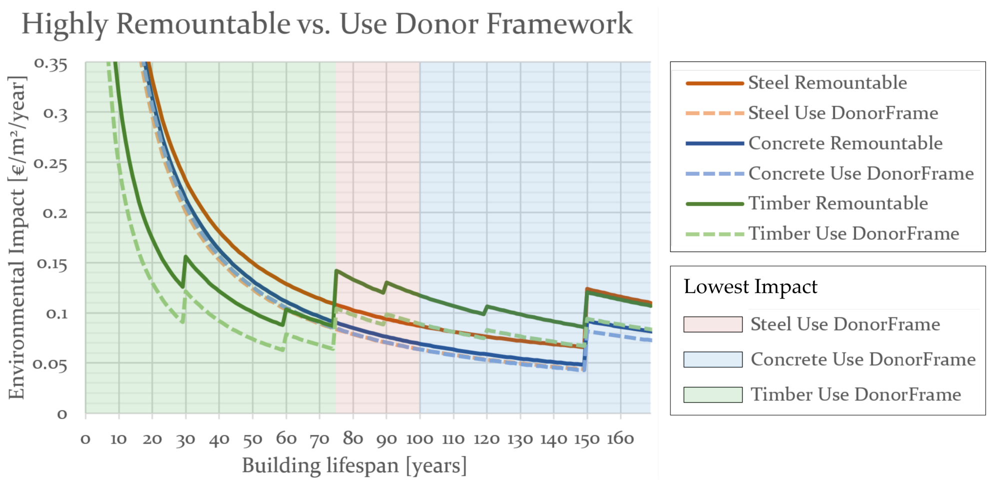

Figure 0.1: Environmental impact of a highly remountable structure vs. a structure where a donor structural framework is used.

In the current design practice of a building, the default lifespan has been determined by the function of the building (Functional Service Life). By using the model developed here, this lifespan can be determined on the basis of sustainability requirements instead of functional requirements. The differences in environmental impact for different lifespans can easily be compared. Therefore, it is made possible to steer towards a certain lifespan, in order to determine the most sustainable construction based on the clients requirements. This is currently not possible in the Dutch construction industry.

However, these results do have their limitations, as they should not be interpreted as general but rather specific conclusions. The following points of attention apply:

- Results should not be interpreted as general results, but these results only apply on the three reference designs as elaborated further in the research. These reference designs are not optimized for every material used.
- Changing input parameters can have a significant impact on the results. In addition, a number of important parameters (reuse percentage, material lifespan etc.) have been assumed due to insufficient existing research.
- The developed allocation equations include the incineration of timber too favorably. This results in a significant deviation in timber environmental impact for lifespans much shorter than 75 years. This flaw can be either due to the model, or the impact parameters as stated in the NIBE EPD app.

Lastly, it is recommended to further research the assumed parameters in this research, especially the material lifespan and the incineration impact parameters. As these parameters can have a major impact on the environmental impact of a specific design.

ACKNOWLEDGEMENTS

This thesis marks the end of my master's program Structural Engineering at Delft University of Technology. During this master I have specialized in Structural Mechanics. A field of study which which enthusiasts me greatly, even though this Master thesis mainly focuses on different aspects of civil engineering.

During my studies I have liked the deepening character of the Structural Mechanics specialization, which has extended my knowledge on specific matter. However, I was missing the chance to dive into a, for me, completely new field of study. I have found that the subject of sustainability has been relatively underexposed during my master's, in comparison with my architectural engineering bachelor. In addition, I have had a great interest, but little knowledge, in the field of parametric design. For this reason, I have chosen to combine these two interesting exciting topics in my master's thesis and therefore delve into two new topics.

This research has been performed in collaboration with and at IMd Raadgevende Ingenieurs in Rotterdam, where I was supervised by Elise van Westenbrugge-Bilardie and Pim Peters. I would like to express my gratitude towards them and all the other people at IMd for their time, effort, critical questions and the great environment, which helped me bringing my research to where it is now.

I would also like to thank the rest of my thesis committee, Jeroen Coenders, Henk Jonkers and Jan Rots. First, I would like to thank Jeroen Coenders for his critical eye and view on the parametric part of my thesis, as well as the rest of White Lioness for helping me with my Grashopper related questions. Furthermore, I would like to thank Henk Jonkers for his extensive knowledge regarding sustainability and the useful sparring sessions we have had over the last year. As my daily supervisor who always had time for me, he has been of great value. At last, I would like to thank Jan Rots as the chairman of my committee, for overseeing the bigger picture of my thesis, without losing the details out of sight.

Then I would like to thank my friends and family who helped me with throughout last year in any form or shape. I would especially like to thank my mom and dad for supporting me and having faith in me, not only during this thesis but my whole life. At last, I would especially like to express my gratitude towards my girlfriend, Judith, for her unconditional support, understanding and advice in both the hard times and the good, while being in the same boat.

Stephan Backx
Rotterdam, February 2020

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ACRONYMS

Part I

Research Framework

1 INTRODUCTION

1.1 MOTIVE

The Programma Aanpak Stikstof (PAS) came into effect on July 1, 2015 and its objective was to improve nature and to speed up the granting of permits. On May 29, 2019, the Council of State ruled that the PAS of the Netherlands did not comply with the European rules. Consequences are big with no fewer than 18,000 projects which can be affected by the ruling [Cobouw, 2019]. Result: A large–scale strike in The Hague by the construction industry. Developments like this, where sustainability is a key factor in the building industry debate, are becoming more common and by now it is clear that climate change is a theme that can not be ignored. Question is, how do we build the future with the least impact on the environment?

Climate change is a problem which occupies humanity to a large extend. In the last century, humanity has intensified the greenhouse effect immensely, due to the emission of greenhouse gasses. A main cause for this increasing rate of emission is due to the consumer focused economy we are living in, a so called linear economy. Products are produced, then used and finally processed as waste. To tackle the enhanced greenhouse effect, it is essential that we make a transition from a linear to a circular economy. The ultimate goal of the circular economy principle is to decouple global economic growth from the extraction and consumption of finite resources. Instead of the use of finite resources, the foundation of economic growth should be the reuse of materials reclaimed from end–of–life products, made possible by designing products for reuse, disassembly and refurbishment [Braendstrup, 2017, p. 7]. To tackle the problem of global warming, it is essential that we make a transition from a linear to a circular economy. The idea of a circular economy is based on three principles [Ellen MacArthur Foundation, 2017].

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

According to Bouwend Nederland, the Dutch building sector is accountable for 20% of the Dutch transport, 35% of the waste and 20% of the energy usage [Bijleveld et al., 2015]. However, the first steps to this circular way of thinking are already taking place. The 2015 Paris agreement led to an agreement in which the Netherlands agreed on a 49% CO_2 emission reduction by 2030 [Vuuren et al., 2017, p. 23]. A logical next step would be keeping the products and materials in use, thus reusing them. The Dutch government is currently transcending into this phase by setting rules in the field of reuseability for the building sector in the form of Life Cycle Assessment (LCA)'s and the Nationale MilieuDatabase (NMD), but this is far from completed.
Of all the different life cycle phases that a building project goes through, the early design phase is the one with the greatest potential for influencing the project and adding value [Khasreen et al., 2009]. A tool which can help implementing the aforementioned reusability in the early design phase could be of great benefit in steering towards sustainable design.

The goal of this research therefore is to develop a tool which can compare designs in the early design phase on their construction material choice from a sustainability point of view. With the help of this tool the most sustainable construction material can be found for different design parameters.

1.2 STATE OF THE ART

To provide an overview on the problem statement in section 1.3, in this section different terms have been elaborated shortly. A more elaborated description and research on all different subjects can be found in the literature study of Appendix A. Firstly, the current state of sustainability in the building industry is discussed. Thereafter, the Life Cycle Assessment principle is elaborated. This method will be used in this research as an approach to quantify the sustainability level of different designs. Afterwards, the term Design for Deconstruction is introduced, a specific idea for implementing sustainable design which is one of the main topics of this thesis. Subsequently, the early design phase is presented, the phase in which the tool is to be used. Then parametric design, a design process using parametric software is introduced and lastly, a quick grasp of existing tools are discussed.

1.2.1 Sustainability in the building industry

The environmental impact of a building over the total lifespan can be divided into its energy consumption and impact of the materials themselves. With 75% to 85% resulting from energy consumption, this part has the largest contribution to the environmental impact. Due to the fact that the Dutch building sector will require all new buildings to be energy–neutral by 2020, this contribution will be reduced. The material–related environmental impact has a smaller contribution with 15 to 25%, but it receives a relatively larger share due to the decrease in energy consumption. Approximately 60% of the materials in a building can be allocated to the load-bearing structure of a building [Silvius, 2016]. For this reason, reducing the material–related environmental impact is primarily focused on the load–bearing structure.

1.2.2 Life Cycle Assessment

In the Netherlands, testing a sustainable building is made up of various steps. Ever since the "Bouwbesluit" was implemented in 2012, it is mandatory to include a calculation for the material–related environmental impact when submitting plans for a building larger than 100 m^2. This calculation is made following the Determination Method of Environmental Impact of Buildings and Civil Works (DM), which was developed by Stichting Bouwkwaliteit (SBK) and is based on the European codes NEN-EN 15804:2012 and NEN-EN 15978 (see Figure 1.1). The method describes how a LCA or Environmental Product Declaration (EPD) calculation shoud be performed in the Netherlands. Results of this method from various construction materials and processes are assembled in one environmental database, the NMD. The user of this database can be sure that the different materials, processes and products are assessed in the same way and therefore can be used to compare design alternatives. In this research an existing LCA and EPD database is used, the NIBE EPD application (app.epdnibe.com).

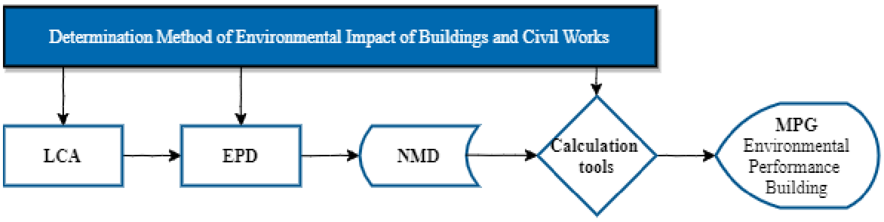


Figure 1.1: Overview of an environmental impact calculation levels in the Netherlands

The NEN-EN 15804:2012 is the European standard on how to perform a Life Cycle Assessment (LCA). This assessment consists of multiple stages, denoted with A (product + construction), B (use), C (end–of–life) and D (beyond–end–of–life) as observed in Figure 1.2. Every stage is divided into smaller scenarios. The first stage is in line with the Cradle2Gate principle, whereas all stages combined are in line with the Cradle2Cradle principle. The result of such an assessment is a product sheet of the total environmental impact of a product/material. This product sheet is called an Environmental Product Declaration (EPD). An EPD is constructed of 11 different Environmental Impact Categories. All these categories have their own weighing factor, a factor which represents the costs to eliminate one kg of its corresponding equivalent unit from the environment. The environmental impact categories are measured in equivalent units. This means that for instance the Global Warming Potential (GWP) is measured in kg CO_2–equivalents. In this equivalent unit not only CO_2 is processed, but also other chemical substances which worsen the GWP, such as NO_2 or CH_4 [Silvius, 2016, p.7]. In the current version of the NMD, version 2.3 during the start of this research, only Cradle2Gate and Cradle2Grave processes are included.

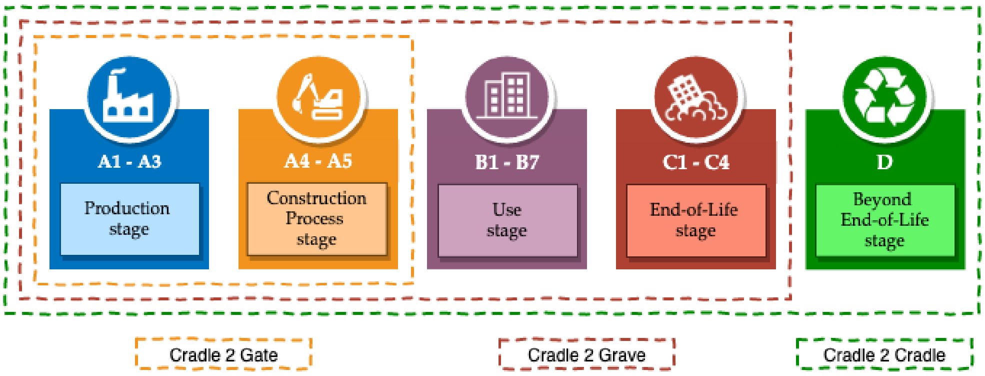


Figure 1.2: Overview of an LCA procedure

1.2.3 Design for Deconstruction and Donor Structural Framework

There are different ways to reduce the aforementioned material–related environmental impact of the load-bearing structure. Regarding the service life of a building two distinct approaches can be distinguished.
Firstly, the total service life of the load–bearing structure can be elongated as much as possible, wherefore the environmental impact of the material is divided over a long period. The building is designed in such a way that if a different function is needed during its functional service life, the structure remains and the building can be transformed.

The second approach is by trying to reuse structural elements as long as possible over multiple lifespans of a building. This is achieved by either implementing the Donor Structural Framework or the Design for Deconstruction (DfD) concept. These concepts aim to increase resource and economic efficiency and reduce pollution impacts in the adaption and eventual removal of buildings, and to recover components and materials for reuse, re–manufacturing and recycling [Guy, 2006]. So these concepts does not aim to maximize the service life of a building, but rather of a structural element or material. This perfectly fits into the circular economy notion. However, calculation rules concerning these concepts are lacking in the Dutch method of determining the environmental impact of a building, the so-called "DM". Therefore, one of the main goals of this research is to implement these concepts in the sustainability calculation. Further information regarding this topic can be found in section A.3.

Reuse of structural elements can happen at the construction phase of a building, or at the end of its lifespan. The first means the use of a donor structural framework when constructing a new building. In this case, old structural elements are reused in a second life cycle. The latter term, DfD, catches the chance that a building that is constructed is being reused as a donor structural framework at its end–of–life phase. The distinction between these two cases is visualized in Figure 1.3.

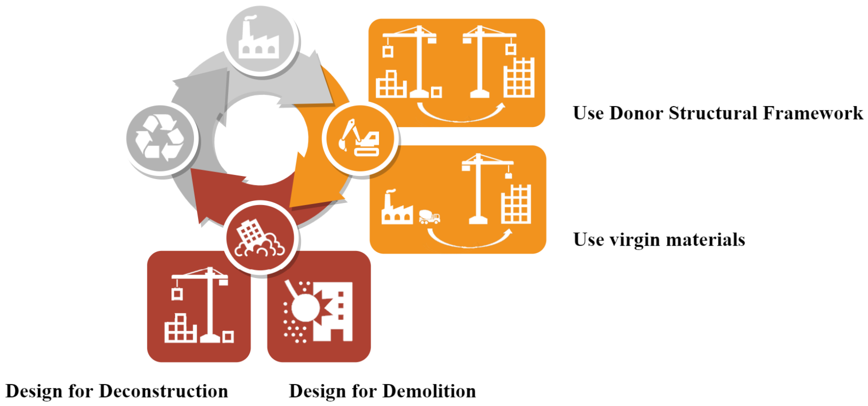


Figure 1.3: Difference in the Donor Structural Framework and Design for Deconstruction concepts.

1.2.4 Preliminary design phase

To achieve truly sustainable solutions, the designers need to have a commitment to achieve sustainability early in the design process so that they are truly embrace it as part of the solution as it is developed. When this is not the case, designers may attempt to make a solution sustainable near the end of the design process. At this point it is too late to have a meaningful impact on the final design because most of the design freedom is gone and changes to the design are very expensive [Roach, 2014]. This phenomena is known as "The MacLeamy curve", which is stated as "The more you learn the less freedom you have to use what you know" and is shown in Figure 1.4. As the figure states, the designers are making the most important decisions in terms of both obtaining a good design and being cost effective when they have the least amount of knowledge about the design problem.

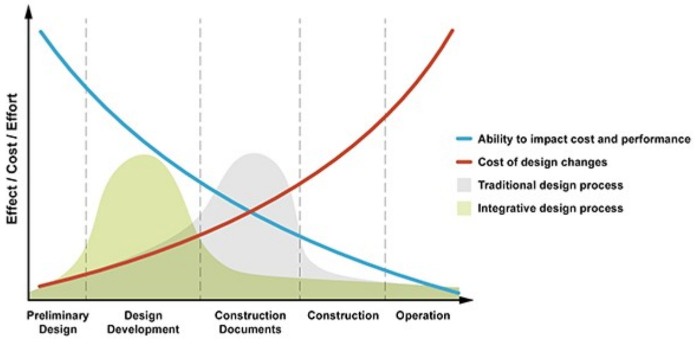


Figure 1.4: The MacLeamy Curve

In the early design phase, choices regarding the type of construction material are made, but due to the limited gained knowledge, these choices are made on a gut-feeling instead of in an argued manner. Default assumptions are made for which material is most sustainable (most people think of timber), but the response to this question is dependent on too many parameters in order to have a normative answer. This can be seen as the "traditional design process" of Figure 1.4. The current method of environmental impact calculation also works in this way and is only made at the end of a design process. This is due to a lot of specific information about the design is being required to make such a calculation, which makes it difficult to quantify sustainability. Existing programs which calculate the environmental impact of buildings like "GPR Gebouw", "MPGcalc" and others are extremely elaborate in terms of usability. Therefore, they are only used in the definitive design phase, instead of the preliminary design phase. This means current design decisions are not taken with exact numbers on sustainability in mind. The solution is to shift current environmental impact calculations to the preliminary design phase, which stated as the "integrative design process" thus steering towards a more sustainable design (and material choices) is made possible.

1.2.5 Parametric design

To make this argued choice of construction material, the design paradox has to be tackled. The goal is to create a system that would be flexible enough to encourage the engineer to easily consider a variety of designs. The cost of making design changes ought to be as close to zero as possible, so without losing the freedom of choice [Linden, 2018]. This is exactly what the use of parametric modeling can accomplish. Parametric engineering implies the use of logic — in the form of algorithms driven by input parameters — as a digital design medium to assess engineering problems [Linden, 2018]. Parametric modeling is a modeling process with the ability to change the model geometry as soon as the dimension value is modified. Parametric modeling is implemented through the design computer programming code such as a script to define the dimension and the shape of the model. The model can be visualized in 3D draughting programs to resemble the attributes of the real behavior of the original project [Feng, 2018].

Scripting the design can be used to quickly evaluate changes in design, without the need to redraw the whole model. This process can also be automated to optimize a certain model or explore multiple designs. Using this scripting, it is also possible to visualize this whole process in such a way that end-users can interact with the model in a user-friendly environment. This method is used to fulfill the goal of this research.

1.2.6 Existing tools

The idea of a parametric tool is not new. In this section, the existing tools regarding the research is divided into two main aspects; calculating the Bill of Materials (BoM) and calculating the environmental impact. As an example, two existing tools are elaborated which, when combined, can form a less advanced variant of the proposed model of this research.

Structural design + BoM → BHH–Model
LCA calculation + EPD → MPGcalc

Current implementations of the different calculations needed to answer the research question are mostly executed in Microsoft Excel. The following tools are used in this research either as a basis for the to be developed model or to validate that model.

Calculating the Bill of Materials

Model BHH: The 'Bepaling Hoeveelheden Hoofddraagconstructie' model is developed by IMd as a method to easily calculate the Bill of Materials (BoM) of a building. The input of this excel model are separated in dimension–related parameters, the main structural system and different inputs regarding all different building layers. The model calculates the BoM based on the Eurocodes and rough calculations used in the preliminary design phase. Model BHH is an open-source tool and is used as a base on which the developed model in this research is formed [Westenbrugge-Bilardie and Peters, 2016].

Calculating the Environmental Impact

MPGcalc: When the BoM is prepared in the BHH model, the material quantities are transferred to the 'MPGcalc' tool, which is a sustainability tool developed by DGMR in order to quickly calculate the sustainability score of a building. This model has the BoM as input, and calculates the environmental impact in [$€/m^2/year$] by using the NMD as a database and the underlying LCA methodology, as explained in Figure 1.1. MPGcalc is free–to–use software which is used in this research as a validation method for the newly developed environmental impact calculation.

Multiple other tools and models exist calculating either the Bill of Materials or the environmental impact. However, none are able to do both and none is able to calculate the environmental impact in the preliminary design phase.

1.3 PROBLEM STATEMENT

Design for Deconstruction is a concept which perfectly fits into the circular economy idea. However, insufficient knowledge regarding the environmental impact of this and the Donor Structural Framework concept is known. When this attitude is taken into account in the environmental impact calculation, a better estimation on the choice for best suited construction material can be formed.

Life Cycle Assessment is a method which quantifies environmental impact of a given product. However, current LCA methodology is made for the linear economy of yesterday, only taking the Production, Construction and End-of-Life phases into account. Question is how to quantify the environmental impact in a circular economy, where the decisions of tomorrow influence the impact of today?

Currently, an LCA is calculated after the global design decisions are made. In this way, an LCA has little to no impact on the design process of a building. Therefore, the choice for the type of construction material is not taken on a scientific basis with environmental impact as a starting point. When this method can be changed into something which is easier to implement without needing to be an LCA expert, this tool will be used much earlier in the design process and material choices can be made in a substantiated way.

The aforementioned can be summed up as follows:

How to choose the preferred construction material in the early design process based on sustainability?

Which can be divided in:

- Insufficient knowledge regarding the environmental impact of the application of Design for Deconstruction and a Donor Structural Framework.
- The Life Cycle Assessment methodology does not consider the beyond end–of–life phase.
- No assessment of sustainability in the early design phase.

2 APPROACH

2.1 OBJECTIVE

The main objective of this research is to address and partly solve the aforementioned problems of section 1.3. The goal is to develop a model which can aid the user in choosing the most sustainable construction material in the early design phase over the total service life of the building. The Donor Structural Framework and Design for Deconstruction concepts are evaluated in this process.

2.2 RESEARCH QUESTIONS

2.2.1 Main research question

The three bullet points of section 1.3 form the base of this research. This research method is based on the philosophy of the Life Cycle Assessment (LCA) method in combination with a parametric model. With the help of these tools a solution to the following main research question should be given.

How can the most sustainable construction material be found in the early design phase, taking the both the Donor Structural Framework as the Design for Deconstruction principle into account?

2.2.2 Sub-research questions

The sub research questions of this research are divided into two main parts. The first part considers the influence of Design for Deconstruction, which is the theoretical side of the research and includes the development of a new method, while the second part considers the development of the parametric model itself.

1. ***How to implement the Donor Structural Framework and the Design for Deconstruction (DfD) concept into the existing LCA methodology?***
   a) *What elements are missing in the current LCA methodology?*
   b) *What other existing methods and concepts can be used to implement and quantify circularity?*
   c) *How should these existing methods be modified such that they include the donor framework and DfD concept?*

2. ***How to assess the environmental impact of a steel, concrete and timber load–bearing structure and their corresponding service lives using a parametric model?***
   a) *Which assumptions need to be made in order to be able to assess the environmental impact using a parametric model?*
   b) *How can the newly established methodology be implemented in a parametric model?*

2.3 SCOPE

Due to the master thesis time limits, the scope of this research needs to be constricted. In what sense is to be determined in cooperation with IMd. Due to this thesis being in line with the master Structural Engineering, the general scope of this research will be limited to the structural aspects only.
In order to make the process realizable in the set time limit, not all varieties of buildings and structural systems will be included.

Subject	System Boundary
Building Type	The building type considered non–residential buildings, mostly aimed at offices and schools. Due to the vacancy of Dutch offices being 10% in 2018, which is the highest of all building types [CBS, 2018] and the future vacancy of schools due to a declining demand [Niaounakis and Hulst, 2017], primarily outside the randstad.
Shape	Only rectangular building shapes are considered, so the width and length are the only parameters for the gross floor area.
Structural elements	A preliminary research will be held to investigate which structural elements (eg. floors, foundation, columns and beams etc.) have the most significant environmental impact. Only these elements will be considered. From [Kuijk and Haalen, 2019] follows the environmental impact of floors is over 60% in general. Regarding the floor system, only concrete hollow–core slabs and timber Kerto–Ripa floor systems are used. This means the steel design has a concrete floor as well.
Foundation type	Design and calculation of the foundation is not taken into account in this research. There are many design variants available in terms of foundation types, which are highly dependent on a single project situation and would drastically complicate the research. However, this is something to look at in further research.
Re-usability	There are two main methods to elongate the service life of a building. The first one being making a durable load-bearing structure, in such a way that the building can be transformed if different functionality is needed. This method is not taken into account in this research. The second method, Design for Deconstruction is taken into account in this research. However, this is not compulsory for an LCA following the NEN-EN 15804.
Materials	In–situ cast concrete (framework), precast concrete (floors), S355 steel (framework) and glued laminated timber (framework + floors). The influence of the service life on the choice for the construction materials mentioned above is considered. Other materials are not considered.
Life cycle scenarios	The construction phase (A) and end–of–life + Beyond end–of–life phase (C + D) are included in this research. The use phase (B) is excluded for this research for multiple reasons. It is assumed that all structural elements are used in an indoor environment, such that maintenance (B2) is not necessary. Repair, replacement and refurbishment (B3, B4, B5) are not taken into account. Finally, operational energy and water use (B6, B7) have no impact on the load-bearing structure so these are not included in this research as well.

Table 2.1: System Boundaries

2.4 GENERAL APPROACH

The main goal of this research is to compare different structural designs based on different materials and their corresponding characteristics. In order to achieve this goal, the approach of Figure 2.1 is followed.

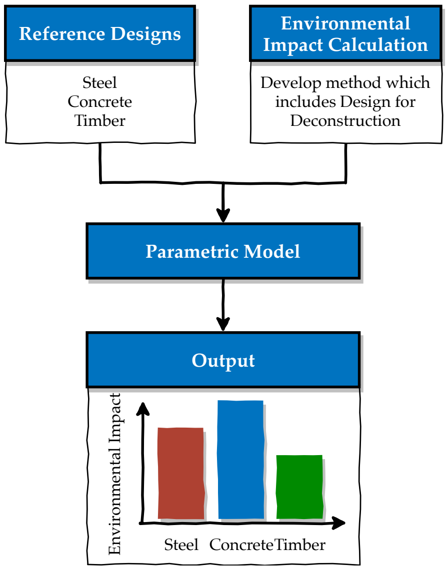


Figure 2.1: The general approach of this research

Reference designs
In order to compare the three different structural materials (steel, concrete and timber), three reference designs are made. These designs have the same assumptions, but are executed in the tree different materials.

Environmental impact calculation
The second main part of the research is based on the development of an environmental impact calculation method which includes the Design for Deconstruction and Donor Structural Framework concepts. These two subjects are combined in one parametric model, in order to quickly generate the environmental impact results for different design variants in the corresponding construction materials and as such give answer to the main research question.

Output
The result of the combination of both aforementioned calculations is the environmental cost for a certain design with specified design criteria.

Due to the fact that the parametric model developed is the integral part of this research and the backbone of this report as well, this is evaluated extensively in section 2.5.

2.5 INTEGRAL PARAMETRIC MODEL

The purpose of the tool is to enable a variant study based on making sustainable design choices. Due to the varying nature of this phase, it was decided to implement the entire required calculation (both structural as environmental costs) in a parametric model. Consequently, if a design parameter is changed, the entire calculation is repeated.

2.5.1 Software

Various software packages have been studied for the use of this parametric backbone. This research uses the parametric environment of Grasshopper in combination with Excel and HumanUI for in– and output purposes as represented in Figure 2.2.

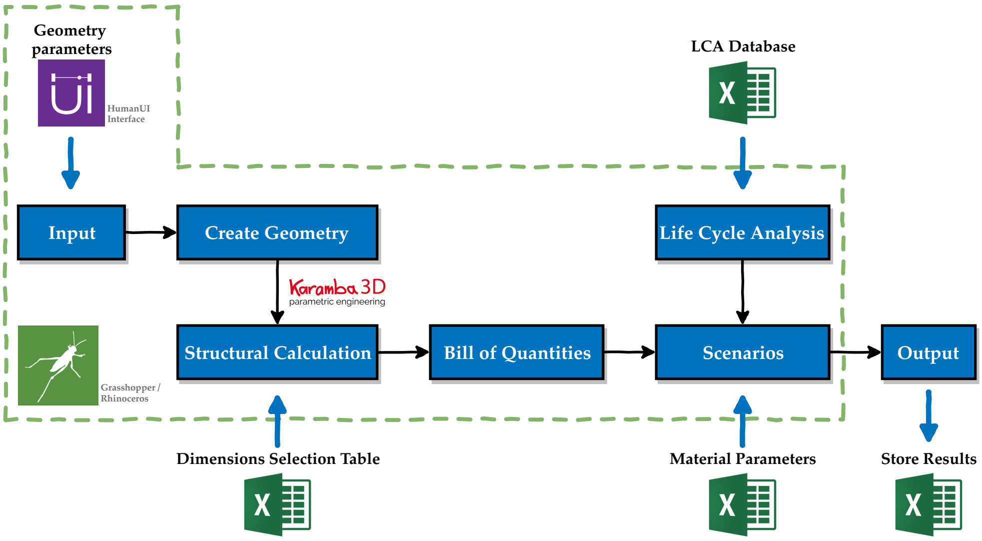


Figure 2.2: Methodology of the model

Grasshopper is an algorithmic modeling plugin for Rhino that uses a visual programming language, developed by David Rutten as an official plugin for Rhino. It is a parametric design tool. For this reason, it is easy to automate things, encapsulate frequent tasks and iterate over different design possibilities. In this research, Grasshopper is used as the base on which the parametric model is built. Different plugins for Grasshopper exist which are used for more specific needs, such as structural optimization (Karamba), creating a user interface (HumanUI) or exchanging information between Grasshopper and Excel (LunchBox/TToolbox). The specific software used in this research in order to develop de parametric model is shown in Table 2.2.

Software	Version
Rhinoceros	6
Grasshopper	1.0.0007 (Built-in in Rhino 6)
Karamba3D	1.15.0.0
TT Toolbox	1.9.6353.28734
Human UI	0.8.1.2
Microsoft Excel	

Table 2.2: Software on which the model is developed.

2.5.2 Detailed parametric model layout

The parametric model which acts as a basis of this research, is split into two main parts:

- Reference Designs
  - *Geometry*
    The three comparable geometries for each material are constructed. The input parameters such as column distance, floor height and amount of floors can be changed in order to change the geometry.
  - *Structural calculation*
    The aforementioned geometries structural members are dimensioned using rules of thumb.
  - *Bill of Materials*
    The size of the geometry together with the size of the members from the structural calculation result in a Bill of Materials (BoM), a list of the amount of kg of every material of every design.
- Environmental Impact Calculation
  - *Life Cycle Assessment*
    Calculates the environmental impact for a certain life cycle phase for 1 kg of a certain material. For instance, the environmental impact in euros for the demolition and disposal of 1 kg C30/37 concrete. The distribution of impact between different life cycles of a building is not taken into account.
  - *End–of–Life Allocation Scenarios*
    Calculates the final environmental impact based on a newly developed allocation method. These equations combine the results of the LCA and BoM.

The total parametric model scheme visualized in Figure 2.3.

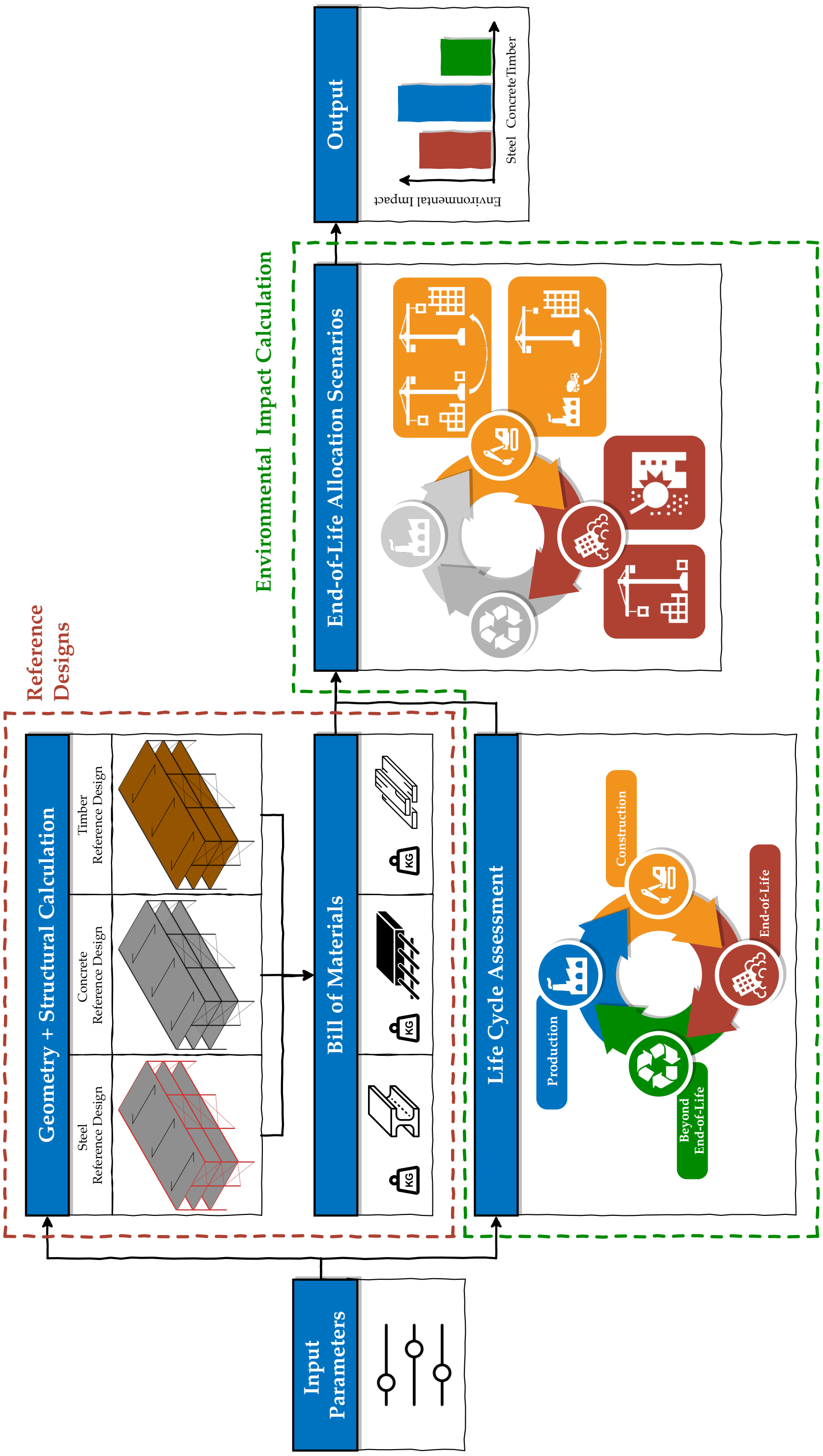


Figure 2.3: The integral parametric model

2.6 THESIS OUTLINE

The main outline of this thesis is based on the integral parametric model of Figure 2.3. The report is divided into three parts. Part I: Research Framework serves as an introduction to the research, and sets the approach. An outline of the two other parts of this thesis is shown in section 2.6.

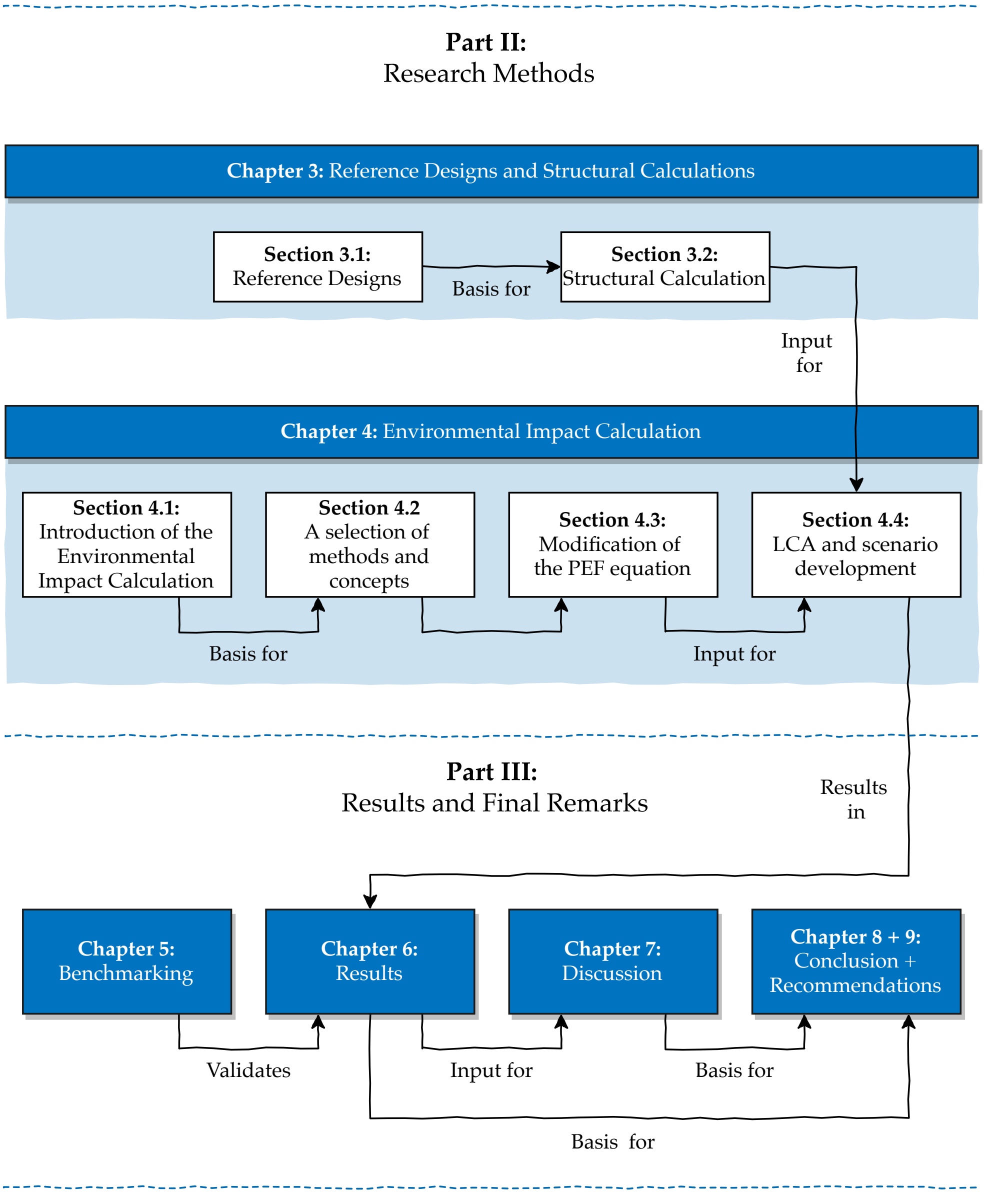


Figure 2.4: Structure of this thesis

2.6.1 Part II: Research Methods

This is the main part of this thesis. In this part the parametric model is elaborated, concepts are introduced and an new end–of–life allocation method is developed. This part is subdivided into two chapters:

Chapter 3: Reference Designs and Structural Calculations
The research is based on the comparison of three different structural materials, which are elaborated and presented in section 3.1. Here, the design requirements are set which form a equivalent basis for the comparison. Furthermore, the geomet-

ric designs per material and their corresponding input in the Grasshopper script are elaborated.

Section 3.2 describes the structural calculation of the reference designs. First, the structural calculation principles are elaborated. Then their corresponding input in the Grasshopper script is explained.

Chapter 4: Environmental Impact Calculation
When the structural part of the research is finished, the environmental impact calculation is introduced. This chapter has the goal to give answer to research question 1: *"How to implement the donor structural framework and the DfD concept into the existing LCA methodology?"* In order to achieve this, the chapter is divided into four sections.

Section 4.1 places the environmental impact calculation in the research and describes the steps taken in the next chapters in order to include DfD in the existing LCA methodology.

Section 4.2 researches and selects different end–of–life methods and circularity concepts. This can be seen as the theory and methodology behind the modification of the existing environmental impact calculation methods. At first, the section defines the missing elements in current LCA methodology. Due to the fact that existing methodology does not take end–of–life allocation into account, the chapter continues with a comparison and selection of these allocation methods. In order to include the missing circularity aspect, the Building Circularity Index is selected and elaborated.

After a end–of–life allocation method is selected in section 4.2, the selected *PEF* method is modified in order to meet the requirements set for this study. That is, include reuse in the allocation equation and more specific, the use of a donor structural framework and the chance of reuse in the future by applying the Design for Deconstruction concept. This process is elaborated in section 4.3.

Lastly, the Environmental Impact Calculation as executed in the parametric model of Figure 2.3 is elaborated in section 4.4. First, the Life Cycle Assessment is elaborated, whereafter the developed allocation method of section 4.3 is rebuilt to include different options as End–of–Life allocation scenarios.

2.6.2 Part III: Results and Final Remarks

Now the research methods have been elaborated, results of the model can be elaborated. This is done in Part III: Results and Final Remarks. First, the results are benchmarked on structural calculations and environmental impact separately in chapter 5. Then, the final results are elaborated in chapter 6 whereafter they are discussed in chapter 7. Finally, an answer to the research questions is given in chapter 8 and some recommendations for further research are stated in chapter 9.

Part II

Research Methods

3 REFERENCE DESIGNS AND STRUCTURAL CALCULATIONS

This chapter introduces the reference designs, the base on which the materials are compared. Their geometry, materialization and structural principles and calculation are discussed.

3.1 REFERENCE DESIGNS

The purpose of this research is to investigate which construction material is the most sustainable given certain design criteria. To be able to compare the different construction materials, reference designs need to be made of each construction material. This section contains the general design requirements, the forthcoming geometries and its materializations. In the parametric model, this is shown as "Geometry", see Figure 3.1.

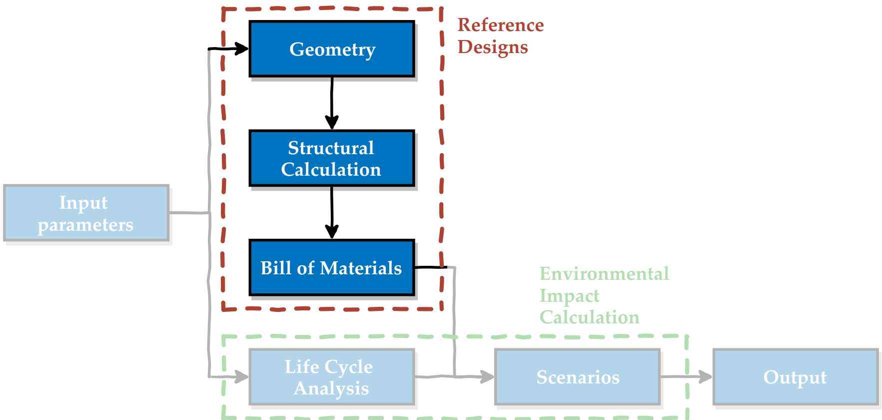


Figure 3.1: Place of the reference designs in the model

3.1.1 Design requirements

The starting point for the design choices of Table 3.1 is the preparation of three designs (steel, concrete, timber) that are as equivalent as possible. Therefore, the designs created are not the optimum designs for the construction material in question, but only as similar as possible to the other two designs. For this reason it has been decided to keep the design principles of all materializations the same.

Subject	Design choice	Explanation
Floorplan	Rectangular grid (x,y)	As a reference design, a rectangular grid is chosen with the same floorplan on every floor. This makes the Gross Floor Area GFA (and therefore functional unit) comparable to not only these three designs but other simple office building designs as well.
General structure	Framework (beams, sleepers and columns)	Due to the building type considered being an office, a framework of beams and columns is the most obvious choice, in contrast to load–bearing walls.
Floors	Hollow–slab floors	Hollow–slab floors are the most used flooring system. This system can be executed in both concrete (VBI) and timber (Kerto–Ripa) which makes the designs more comparable.
Connection type	Hinged	In order to be able to apply the Design for Deconstruction concept.
Stability system	Bracings	In general, the most used stability system for steel and timber buildings is the use of bracings, whereas concrete buildings mostly use a stability core. However, a concrete core also acts as a wall within the design, which is not apparent in the steel and timber designs. This means the functional unit of both designs is not equal. For this reason and the comparative purpose of the designs, it is chosen to brace the concrete design as well.

Table 3.1: Design choices made in order to have three comparable designs.

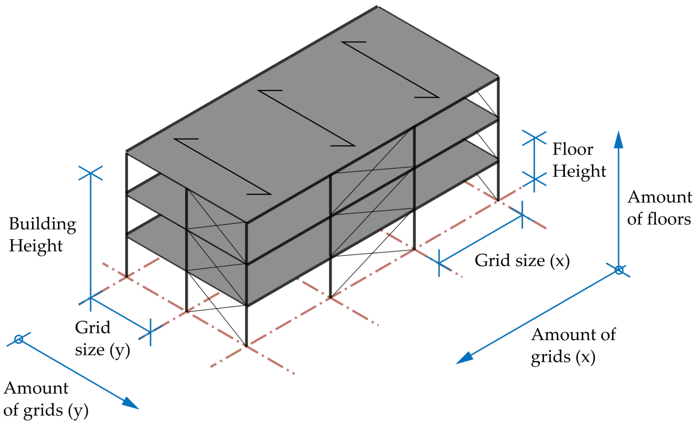
3.1.2 Geometry and case–study

The reference designs are scripted in the parametric environment of Grasshopper. This means, parameters such as floor height, grid size, amount of grid lines, number of floors et cetera are all variable in the model.

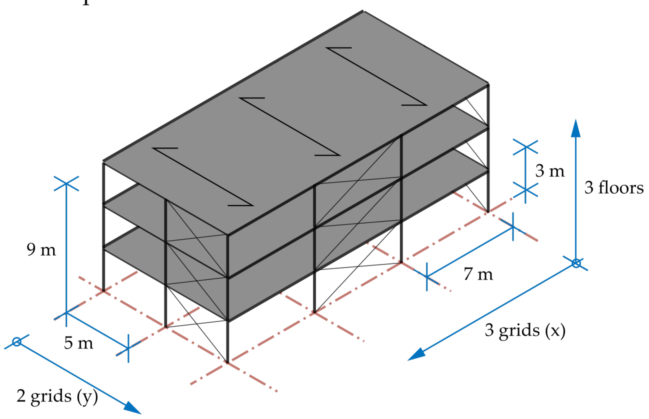
Table 3.2 describes per variable whether they are used dynamically or if they are fixed. The table distinguishes the parametric model and the case–study. The parametric model represents the eventual tool, where different designs can be evaluated by the ease of changing a slider. However, in order to compare and validate the reference designs and their outcomes in this report, an arbitrary case–study is constructed which has fixed parameters. The corresponding geometry of Figure 3.2b and its dimensions are used throughout this report.

Parameter	Unit	Use in parametric model	Use in this report (Case–Study)
Grid size (x)	m	Dynamic	7
Grid size (y)	m	Dynamic	5
Number of axes (x)	-	Dynamic	3
Number of axes (y)	-	Dynamic	2
Number of floors	-	Dynamic	3
Floor height	m	Dynamic	3
Gross Floor Area	m^2	Dynamic	630

Table 3.2: Parameters related to the geometry and their use in the parametric model or the case–study.



(a) Dynamic geometric properties of the reference design, used in the parametric model.

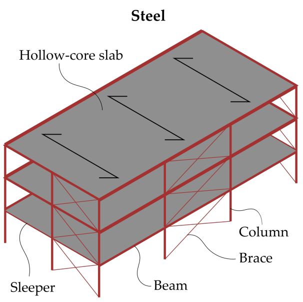


(b) Static geometric properties of the case–study, as used in this report.

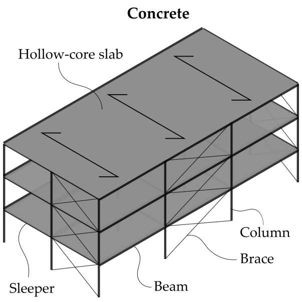
Figure 3.2: Geometric properties of both the parametric design and the static case–study. A floor height of three meter could be inadequate. However, this only is a case–study and the actual model is fully parametric, which enables quick modification of the dimensions.

3.1.3 Reference design per material

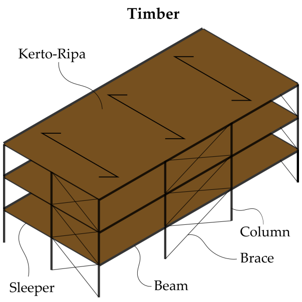
Table 3.3 shows the materials and systems chosen regarding the different designs of Figure 3.3. As mentioned before, every design follows the same design principles set up in subsection 3.1.1.



(a) A steel frame in combination with hollow–core slabs without concrete topping and steel braces.



(b) A concrete frame with precast hollow–core slabs and steel braces.



(c) A timber frame with steel braces and Kerto–Ripa flooring and roofing.

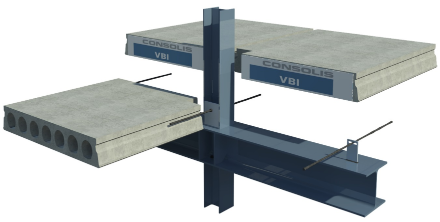
Figure 3.3: Three reference designs which are compared using the parametric model.

	Steel	Concrete	Timber
Roof	VBI Hollow–core slab	VBI Hollow–Core slab	MetsäWood Kerto–Ripa
Floors	VBI Hollow–core slab	VBI Hollow–Core slab	MetsäWood Kerto–Ripa
Bracings	S355 L	S355 L	S355 L
Beams	S355 IPE	Precast C30/37 + B500B	GL28h
Sleepers	S355 IPE	—	GL28h
Columns	S355 HEA	Precast C30/37 + B500B	GL28h

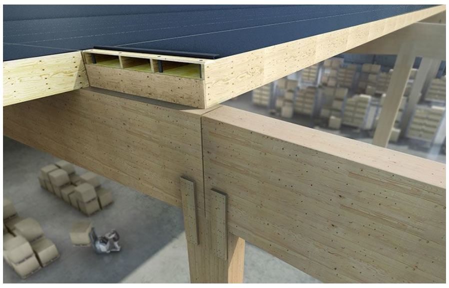
Table 3.3: Choice of building materials of the three reference designs.

Roof and floors

For the concrete hollow–core slabs used in the steel en concrete design, the "VBI PV Hollow–Core slab Green" type is chosen, due to its relatively low environmental impact [VBI, 2013, 2019b]. These hollow–core slabs can act as a rigid floor diaphragm with the use of tension rods, so they do not need a compressive layer. Hence, this system is easier to demount as a classical hollow–core slab flooring system.
Since the goal is to compare different materials equally, it is chosen to implement a similar floor system in the timber design. The Kerto–Ripa Box floor system of MetsäWood. As both of these systems are bolted into place, they are completely remountable and thus fit into the Design for Deconstruction (DfD) concept. Both these systems are shown in Figure 3.4a and 3.4b respectively. The recesses in floors due to stairwells and elevator shafts is assumed similar for every design, so these are neglected in the model. This means the GFA of every design is similar but not perfectly realistic.



(a) Concrete and steel floor/roof system VBI hollow–core slabs [Bouwwereld, 2018].



(b) Timber floor/roof system MetsäWood Kerto–Ripa Box [Kennisbank Biobased Bouwen, 2019].

Figure 3.4: Hollow–Core slabs of both VBI (concrete) and MetsäWood (timber).

Bracings

As mentioned before, every design has the same stability system. Steel L–shaped bracings are used everywhere due to their ease–of–use.

Beams, sleepers and columns

The steel beams, sleepers and columns are formed of hot rolled profiles in S355 strength grade. Furthermore, the concrete design is executed in a precast C30/37 strength grade, in addition of B500B reinforcement steel. In general, In–situ cast concrete has a lower environmental impact than its prefab counterpart, due to the fact that the latter needs a higher percentage of cement for rapid hardening and formwork removal. However, in this design prefab concrete is used in order to be able to apply the Design for Deconstruction concept. No sleepers are needed for the concrete design.

With the office function of this project in mind, bigger spans than five meter are expected. As regular timber can not compete with a steel and concrete framework in terms of the possible length of the spans and the goal is to equally compare the different materials, it is chosen to execute the timber beams, sleepers and columns in glued laminated timber. As such, similar spans as steel and concrete can be achieved, at the cost of a higher environmental impact relation to regular timber. The choice to not place extra columns in the wooden design is a deliberate one, in order to keep the designs as similar (and therefore maybe not as equivalent) as possible.

3.1.4 Geometry grasshopper input per design

The reference design geometry is modeled in Grasshopper per material, such that every material has its own geometric properties. The total Grasshopper script is elaborated and explained in Appendix H, while the geometric part is discussed in subsection H.3.1. The geometry is divided in a general structural framework, bracings and floorbracings part.

The framework constructs a 3D grid and connects the nodes in order to create columns, beams and sleepers in Figure H.5. After this, the framework is braced vertically by connecting outer nodes diagonally in Figure H.6. The floor bracings ensure the rotational stability of the structure, as shown in Figure H.7. In real–life this is accomplished by the diaphragm action of the hollow–core slabs but this is modeled by floor braces.

3.1.5 Conclusions

A standard reference geometry has been drawn up in order to be able to make a comparison that is as equivalent as possible. This geometry serves as the starting point for the designs of the various construction materials. For this reason, the functional unit of each design is equal.

3.2 STRUCTURAL CALCULATIONS OF THE REFERENCE DESIGNS

The geometry and materialization of every reference design is discussed and elaborated in section 3.1. This section follows up to that section as the dimensioning of every structural element described in Table 3.3 is executed here. As a reference, the dimensions of the case–study from Table 3.2 are taken as the starting points of these calculations.

3.2.1 Structural calculation per design

The structural designs are based on the geometries of Figure 3.2. All nodes (so all connections) are assumed hinged due to the Design for Deconstruction concept being applied, which means only single spans are used in this design. The structural calculation principles as used in the parametric model are shown in Table 3.4.

	Steel	Concrete	Timber
Floors	Rules of thumb (Model BHH)	Rules of thumb (Model BHH)	Rules of thumb (Ripa Schuif)
Beams, sleepers and columns	Rules of thumb (Jellema)	Rules of thumb (Jellema)	Rules of thumb (Jellema)
Bracings	Optimized (Karamba)	Optimized (Karamba)	Optimized (Karamba)

Table 3.4: Structural calculation principles

As shown, most structural elements are based on Rules of Thumb, either from the BHH–model [Westenbrugge-Bilardie and Peters, 2016], or Jellema [Hofkes et al., 2004]. Both options are generally available (either to purchase or for free). The rules of thumb used for the dimensioning of the structural framework are elaborated in Table 3.5. Due to the relatively small weight of the bracings, these are neglected in the total Bill of Materials (BoM).

Note: Due to the fact that the designs are dimensioned based on rules of thumb, both the horizontal and vertical loads are not required, except for the floors taken from the BHH–model. In Grasshopper, only steel structures can be structurally optimized in a user–friendly manner. However, this deemed not possible for the concrete and timber model. Due to the required uniformity in calculation methods and profoundness, it is chosen to only use rules of thumb in this research. However, a quick comparison has shown that the difference in an optimized steel structure versus a steel structure dimensioned by rules of thumb is fairly small ($\pm$ 10%).

Member	**Rule of Thumb (variable in the model)**	**Case–Study result**	**Applied in Case–Study**
		Steel	
Beam	$\frac{h}{l} = \frac{1}{15}$	$h = \frac{7000}{15} = 476$ mm	IPE500
Sleeper	$\frac{h}{l} = \frac{1}{20}$	$h = \frac{5000}{20} = 250$ mm	IPE270
Column	$\frac{1}{12} l_{buckling}$	$d = \frac{3000}{12} = 250$ mm	HEA260
		Concrete	
Beam	$\frac{h}{l} = \frac{1}{10}$	$h = \frac{7000}{10} = 700$ $b = \frac{h}{2} = 350$	700x350
Sleeper	$\frac{h}{l} = \frac{1}{15}$	$h = \frac{5000}{15} = 333$	350x150
Column	$\frac{1}{35}\sqrt{n} \cdot l_{buckling}$	$h = \frac{1}{35}\sqrt{3} \cdot 3000 = 149$	150x150
reinforcement	$\rho = 0.01$	$\rho = 0.01$	$\rho = 0.01$
		Timber	
Beam	$\frac{h}{l} = \frac{1}{15}$	$h = \frac{7000}{15} = 467$ $b = \frac{h}{6} = 78$	495x115
Sleeper	$\frac{h}{l} = \frac{1}{20}$	$h = \frac{5000}{20} = 250$ $b = \frac{h}{6} = 42$	270x56
Column	$\frac{1}{25} l_{buckling}$	$h = \frac{1}{25} 3000 = 120$	120x120

Table 3.5: Rules of thumb steel reference design [Hofkes et al., 2004], for original rules of thumb, see Appendix D.

The rules of thumb of Table 3.5 have been applied to the mechanics model as schematized in Figure 3.5.

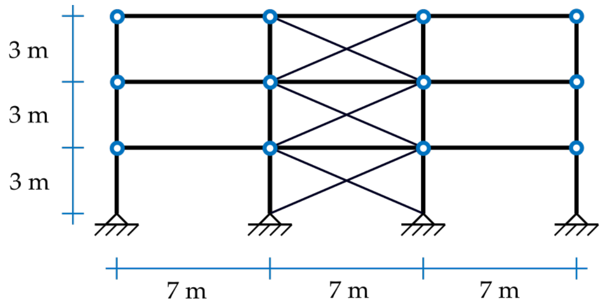


Figure 3.5: The mechanics scheme as used in the model, with hinged connections. Dimensions and number of grids differ in x and y directions, but the mechanics scheme is similar.

Roof and floors

The structural calculation of the floor systems described in Table 3.1 are based on product info from the manufacturer. The VBI concrete hollow–core slabs are designed with the Bepaling Hoeveelheden Hoofddraagconstructie (BHH) model, while the timber MetsäWood Kerto–Ripa floors are designed by the online tool Ripa Schuif. For both these floors, a load of $Q_{qk} = 5\ kN/m^2$ is assumed. The results of those calculations are shown in Figure D.2 and D.6.

3.2.2 Structural calculation grasshopper input per design

The structural calculation is modeled in Grasshopper per design. The total Grasshopper script is elaborated and explained in Appendix H, while the structural calculation part is discussed in subsection H.3.2. The structural calculation is divided into three groups; the element assembly, dimensioning of structural elements and the bill of materials for the corresponding material.

The element assembly script, visualized in Figure H.8, divides the lines constructed by the geometric structural framework (subsection 3.1.4) into six groups; roofbeams, beams, sleepers, columns, bracings and floorbracings, whereafter the elements are created per group. Every node of the framework is modeled as a hinged connection and the supports are modeled as well. At last, the materials neccesary for every structural design are created. After the element assembly, every element group is dimensioned based on the rules of thumb as shown in Table 3.5. At last, the BoM is created by summing up the weights per element group. This procedure is executed for every material of every reference design.

3.2.3 Conclusions

Now the structural design principles are set, sub–research question 2a can be answered:

"Which assumptions need to be made in order to be able to calculate the environmental impact using a parametric model?"

- A geometry is assumed of which the structural calculations are made. This geometry is assumed equal across all designs in order to compare all results equally.
- Due to the fact that the tool is to be used in the early design phase, no detailed structural calculations are required. Together with the fact that Grasshopper in its current form is not able to optimize concrete and timber structures in a user–friendly way, it is chosen to base the structural calculation of the three designs on rules of thumb.

Now that the reference designs have been erected in a parametric manner, the first part of the tool is completed. This chapter has mostly defined the research, and therefore acts as a preparation for chapter 4. The result of this chapter is the completed BoM, where the total amount of every material is joined. This bill of materials acts as input for the next part of the tool, the Environmental Impact Calculation, which is developed in chapter 4.

4 ENVIRONMENTAL IMPACT CALCULATION

4.1 PLAN OF ACTION TO INCORPORATE REUSE CONCEPTS

This chapter describes and elaborates the main part of this research. It answers the question of how to include the Design for Deconstruction concept in current Life Cycle Assessment (LCA) methodology and executes this newly developed method in a parametric manner.

4.1.1 Place of the environmental impact calculation in this research

The main part of this research is based on finding the influence of Design for Deconstruction on the environmental impact of a building. A schematic representation of the parametric model is shown in Figure 4.1, where the environmental impact calculation is highlighted.

This chapter is divided into three main sections. First, a selection of applied methods and concepts is made in section 4.2. Subsequently, the chosen End–of–Life (EoL) allocation method is modified in order to include the Design for Deconstruction concept in section 4.3. Lastly, the Life Cycle Assessment of the reference designs is taken care of in section 4.4, together with the development of the EoL scenarios. This last section describes the actual input for the parametric model as shown in Figure 4.1.

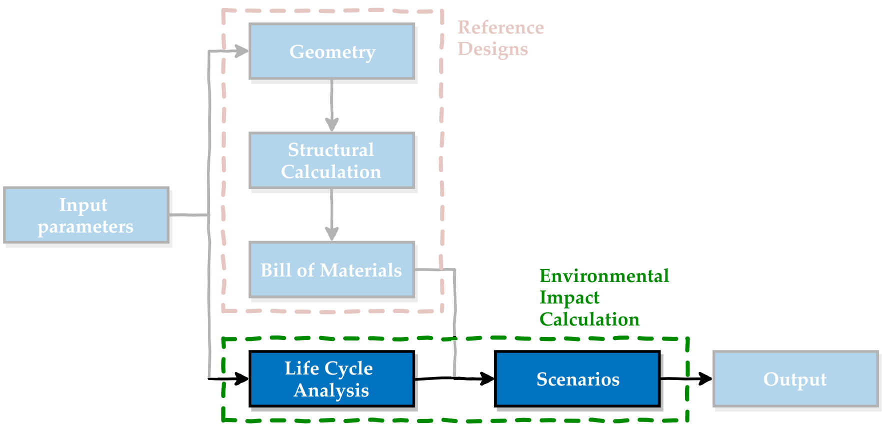


Figure 4.1: Place of the environmental impact calculation in the model

4.1.2 Steps needed in order to include Design for Deconstruction in existing LCA methodology

In order to include the Design for Deconstruction (DfD) into the LCA methodology, several steps have to be taken. These steps can be summed up as follows:

1. *Which requirements are missing in the existing methodology?*
   The goal of this research is to develop a method which does not only consider current life cycle, but the previous and next one as well. For this reason, multi-

ple requirements are needed which are not involved yet. These requirements are identified first.

2. *Selection of methods and concepts based on selected criteria.*
   There are multiple existing methods on how to include multiple life cycles in an Environmental Impact Calculation (EIC). These are called end–of–life (EoL) allocation methods. After the gaps in current methodology are considered, a selection of existing methods and concepts is made, which are used as a base for the newly developed EoL allocation method.

3. *Adjust chosen method/equation in order for it to comply to all set requirements.*
   As mentioned, the chosen allocation method forms a base, but has to be modified to meet all requirements set for this research. These modifications add the following elements to the allocation method:
   a) *Reuse*
   b) *Remaining Service Life*
      How long can the service life of a material be expanded after the building is end–of–life?

4. *Create different scenarios in order to include both the Donor Structural Framework as the DfD concept.*
   After reuse in general has been implemented, this aspect is further specified as DfD. First, DfD can be applied during the construction phase of a building, in the form of the use of a donor structural framework, in order to reuse structural elements. In addition, there is the option apply DfD at the end–of–life phase of the building, where the building itself is used as a donor framework for the next building. This must be taken into account during the design phase by making a remountable design. Both scenarios have been elaborated in this study and implemented in the created allocation method.

4.2 A SELECTION OF METHODS AND CONCEPTS

In this section the first two points of subsection 4.1.2 are delineated. First, the missing elements in the current methodology are found in subsection 4.2.1. Alongside a literature research has been performed in order to get more insight into sustainability in general. Then, different existing end–of–life allocation methods are compared and one is chosen in subsection 4.2.2. After that, the problem on how to quantify the circularity (and therefore the probability of reuse) is being tackled in subsection 4.2.3. Lastly, conclusions are drawn on which the modification in section 4.3 is based.

4.2.1 Missing elements in the current LCA methodology

section 1.2 already discussed the subject of sustainability, Life Cycle Assessment and its stages and the definition of the Design for Deconstruction concept. This section continuous on that section. The information presented here is a summary of the literature study performed on sustainability in the building industry, which can be found in Appendix A.

4.2.1.1 *Life cycle phases*

The current LCA methodology is based on Product Category Rules (PCR). These rules define different life cycle stages. An overview of the PCR of a building is shown in Figure 4.2. Different life cycle phases are accentuated with different colors, while the different processes are coded with a letter and number, such as "Raw material supply: A1". Life Cycle Assessments of different life cycle stages and processes of many products are stored in the NIBE EPD app. This system is elaborated further in Appendix A. An example of the NIBE EPD app is shown in Figure G.1.

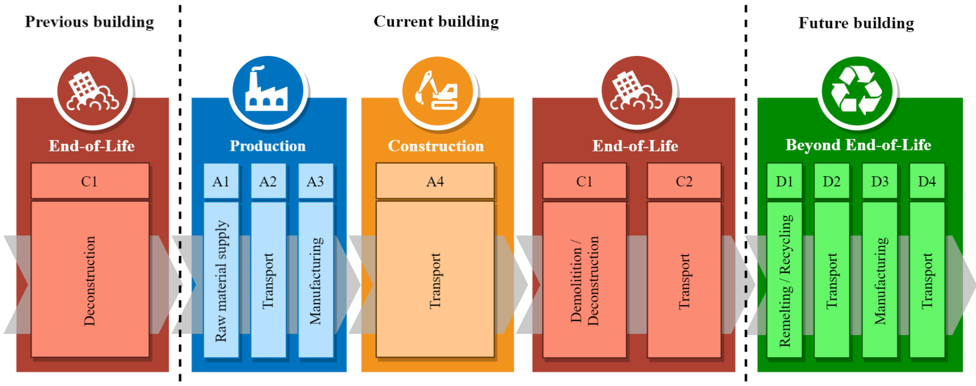


Figure 4.2: Product Category Rules with multiple life cycles of a building included.

In Figure 4.2 the different stages for different life cycles of a building are shown, which introduces the problem visualized in Figure 4.3. The NIBE EPD app houses lots of environmental product data en processes.

However, this data is aimed at single use of a product, the so-called linear use. This can be seen in Figure 4.2 as the phases within the "Current building" area. The impact of producing a new product, transporting it and finally demolishing and waste–processing all make up this cycle. However, when reuse from a previous life cycle ("Previous building") or reuse in a next life cycle ("Future building") must be included, this becomes entirely different matter. The question of what the impact is of dismantling and reusing an element is becoming important. In addition, the question is how much of the impact of reuse is attributed to the "Current building" or the "Future building", where the product is actually reused.

Figure 4.3 shows the different processes when looking at the different life cycles of a construction material, and shows whether this data has already been processed in the NIBE EPD app or not. An answer to the above questions will be sought in the coming sections.

Note: During this research the NIBE EPD app has been updated in order to include different Waste Scenarios for certain materials. Figure 4.3 shows the original app ass used in this research, thus not including the waste scenarios.

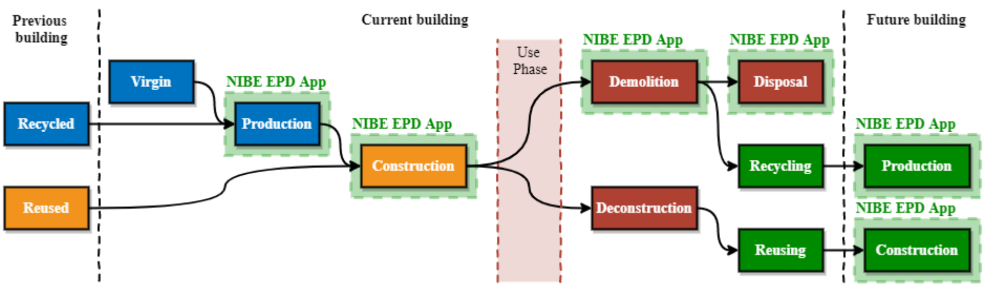


Figure 4.3: Included and missing life cycle phases from the NIBE EPD app. Colors correspond with the life cycle phase colors or Figure 4.2.

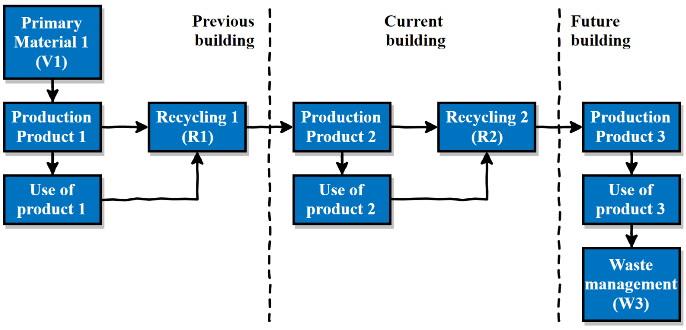
4.2.2 End–of–Life allocation methods compared

Due to this research being focused on the second and third level of circularity (Reuse and Recycling), level one circularity: Transformation is left out (see subsection A.3.1 for more information). This means the impact of both reusing and recycling needs to be calculated. As mentioned in subsubsection 4.2.1.1, the problem of how to allocate the environmental burden of the next life cycle into the current one needs to be tackled. This phenomena is called end–of–life allocation, hereafter EoL allocation.

In order to level out every material on its ability to be either reused or recycled or its durability performance, different EoL approaches are researched in this section. How to allocate the end–of–life and beyond end–of–life phase into an LCA is one of the most controversial subjects of the LCA methodology. This section gives an brief summary regarding the literature research executed in the field of EoL allocation and briefly compares different allocation methods. Lastly, the Product Environmental Footprint method is chosen on which forthcoming chapter, section 4.3 is based. For a more elaborated and substantiated study on this matter, reference is made to Appendix B.

4.2.2.1 *General allocation concepts*

In general, there are a few allocation concepts in use, which all have their pro's and con's. In Figure 4.4a a general life cycle cascade of a building product is shown. Based on this flowchart, different allocation concepts are introduced. The scientific paper of Nicholson et al. [Nicholson et al., 2009] is used as a basis for these concepts, but every to be considered method is verified by other researches. The considered methods are summarized in Figure 4.4b and evaluated below. Different methods are preferred for different construction materials, due to the fact that some methods favour certain materials.



(a) Life cycle cascade of product material flows and processes involving open loop recycling for 3 life cycles [Nicholson et al., 2009, p.2]

Method	Description	Formula
Cut-off method	Loads directly caused by product are assigned to that product [13].	$L1 = V1,\ L2 = R1,\ L3 = R2 + W3$
Loss of quality method	Assigns load to products in relation to their relative loss of quality in each step [13].	$L_i = \frac{Q_i}{\sum_{i=1}^{n} Q_i} \times (V1+R1+R2+W3)$
Closed loop method	Applicable to materials that do not experience significant losses in quality when recycled [14].	$L1 = L2 = L3 = \frac{V1 + (R1+R2) + W3}{n}$
50/50 method	Virgin material production and waste treatment are allocated to the first and last products in equal proportions [13, 15].	$L1 = \frac{V1+R1+W3}{n\text{-}1}$, $L2 = \frac{R1+R2}{n-1}$ $L3 = \frac{V1+R2+W3}{n-1}$
Substitution method	Recycled material substitutes primary; accounts for lost material and recycling burdens [16].	$L1 = (100\%\text{-}r\%) \times (R1) + r\% \times (V1+W3)$
Qi is the quality of material (quality ratios can be computed using market pricing data for primary and scrap materials), n is the number of life cycles, and r is the amount of primary material needed in secondary material production to account for lost material in the recycling process.		

(b) Description and formulas for different EoL allocation methods, variables as described in Figure 4.4a and defined below [Nicholson et al., 2009, p.2].

Figure 4.4: General allocation concepts compared, where 50/50 method is selected.

The **50/50 method** approximation is good when the flows of cascade material to and from the life cycle investigated are small compared to the total flow in the market, the recycling rate is decided by economic forces, and the demand and supply are equally elastic. This method is relatively easy to adept and is widely used as a method to compare different materials. However, this might not be the most realistic allocation method available, due to its strict 50/50 allocation distribution.

4.2.2.2 *The Product Environmental Footprint method*

Allacker et al. compared three international methods (and seven associated equations) in [Allacker et al., 2014], based on the EU policy initiatives stated in subsection A.1.2. Based on the analysis and comparison of these methods in that paper, the multi–criteria table of Table 4.1 is found. The blue rows reflect the important criteria for this research. In order to compare different materials on their sustainability level, it is preferred to have one general formula which can be used for the sustainability calculation of all materials. The Product Environmental Footprint (PEF) method is such a method with a 'one formula fits–all' approach and therefore is chosen as the base end–of–life allocation equation.

Criteria	PAS-2050 (RC)	PAS-2050 + ISO/TS 14067 (CL)	ISO/TS 14067 (OL-LoQ)	BPX 30-323-0 (CL)	PEF	REAPro recyclability	REAPro Energy Recoverability	REAPro (CO)
1. Comprehensiveness	No	No	No	No	Yes	No	No	No
2a. Accomodates Open-loop product system	Yes	No	Yes	No	Yes	Yes	NA	NA
2b. Accomodates closed-loop product system	No	Yes	No	Yes	Yes	Yes	NA	NA
3. Distinguishes % virgin/recycled content input	Yes	No	Yes	Yes	Yes	Yes	NA	NA
4a. Considers recyclability rate	No	Yes	Yes	No	Yes	Yes	NA	NA
4b. Considers energy recovery	No	No	No	Yes	Yes	NA	Yes	NA
5a. Includes material credits	No	Yes	Yes	Yes	Yes	Yes	NA	NA
5b. Includes energy credits	No	No	Yes	Yes	Yes	NA	Yes	NA
6. Account for changes in inherent properties of materials and/or down-cycling	No	NA	Yes	NA	Yes	Yes	NA	NA
7. Avoids double counting at a system level	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8. One formula fits-all	No	No	No	No	Yes	No	No	No

Table 4.1: Summary of the comparison of the production/EoL equations against the eight analysis criteria, regarding [Allacker et al., 2014]. Blue rows reflect the important criteria.

Background information regarding the PEF method can be found in section B.4. The PEF equation is shown in Equation 4.1. An explanation of each parameter can be found in Table 4.3. The elaborated 50/50 allocation method of Figure 4.4b shows in this equation as the $\frac{1}{2}$ factors before most parameters.

$$\begin{aligned} PEF = &(1-\frac{1}{2}R_1)\cdot E_V + \frac{1}{2}R_1 \cdot E_{recycled} + \frac{1}{2}R_2 \cdot (E_{recycling,EoL} - E_V^* \cdot K) \\ &+ R_3 \cdot (E_{ER} - LHV \cdot X_{ER,heat} \cdot E_{SE,heat} - LHV \cdot X_{ER,elec} \cdot E_{SE,elec}) \\ &+ (1-\frac{1}{2}R_2)\cdot E_D - \frac{1}{2}R_1 \cdot E_D^* \end{aligned} \tag{4.1}$$

4.2.3 Measuring circularity with the Building Circularity Index

The selected EoL allocation method, PEF, does not include reuse. The purpose of this research is to include reuse at the end–of–life phase into the environmental impact calculation. Therefore, the probability of structural elements of a building being reused in the future needs to be examined. For this reason, the Building Circularity Index (BCI) is elaborated.

The BCI is derived from the Material Circularity Indicators of the Ellen Macarthur Foundation research of [Ellen MacArthur Foundation, 2013], which are material indicators in general. These indicators were applied by Verberne in his research to develop a specific method to quantify the circularity of buildings, the BCI. This index is further developed by Alba Concepts in order to implement the index into the Dutch material passport, Madaster. This implementation is elaborated in [Madaster, 2018] and [Alba Concepts, 2019]. Due to the development of Madaster continuing and its impact in the Dutch building industry increasing, the BCI method is chosen as the approach to quantify the circularity of a building. The method works as follows:

$$BCI = MI \cdot RI \tag{4.2}$$

with:

$$\begin{aligned}
MI &= \text{Material Index} && = 1 - LFI \cdot F(n) \\
RI &= \text{Releasability Index} && = CT \cdot CA \\
LFI &= \text{Linear Flow Index} && = \frac{\text{\%Virgin material} + \text{\%Loss material}}{2} \\
F(n) &= \text{Use factor} && = \frac{0.9}{n} \\
n &= \frac{TSL}{RSL} \\
CT &= \text{Connection Type} \\
CA &= \text{Connection Accessibility}
\end{aligned}$$

Connection Type (CT)	Value	Connection Accessibility (CA)	Value
Clicked	1.0	Accessible	1
Bolted	0.8	Accessible extra actions without damage	0.8
Pinned	0.6	Accessible extra actions repairable damage	0.6
Kitted	0.2	Accessible extra actions irreparable damage	0.4
Welded	0.1	Inaccessible	0.1

Table 4.2: Connection Type (CT) and Connection Accessibility (CA)

The building circularity is stated as a number between 0 and 1, which represents the "degree of circularity" of a building.

- A building that is entirely constructed from new materials, which has a lifespan shorter than the average lifespan of buildings and totally ends up as waste, is a "linear" building and scores low on the BCI: $(0 - 0.1)$.

- A building that entirely consists of recycled materials or products and can be fully reused in the future is a fully "circular" building and scores high on the BCI: (1). Even if the lifespan is shorter than the average lifespan [Madaster, 2018].

In this research it is assumed that the degree of circularity, calculated according to the BCI methodology represents the probability a building is (partly) being reused in the future. Futhermore, a simplified method of the BCI is used. Usually, a building has a circularity–score on multiple levels (building, element, material etc.). These are then summed up in order to get to the total circularity–score. In this research, a general Connection Type (CT) and Connection Accessibility (CA) are assumed, which results in a single circularity–score. This number is then assumed as the total BCI of the building, and thus the probability that a building is is being reused in the future, hereafter stated as "probability of future reuse".

4.2.4 Conclusions

Conclusions can be drawn based on sub-research question 1a and 1b:

What elements are missing in the current LCA methodology in order to implement circularity?

- Current methodology only aims at the current life cycle of a product, the so called Cradle2Grave approach. The amount of impact of a previous life cycle (Donor Framework) or a future life cycle (Design for Deconstruction) is not taken into account, the so called Beyond–End–of–Life phase, see the note in subsubsection 4.2.1.1.
- The total amount of impact of a certain process is included, but the weighing factors of each process is not included, the so called End–of–Life allocation.

What other existing methods and concepts can be used to implement and quantify circularity?

- It is chosen to implement the reuse and recycling percentages into the existing LCA method with the use of the Product Environmental Footprint method. As can be seen from Equation 4.1, the PEF method uses a 50/50 allocation approach. It includes the same life cycle stages as the original LCA methodology, thus existing life cycle impact values from the Nationale MilieuDatabase (NMD) can still be used. The original PEF method does not include reuse by default, but this is included in section 4.4.
- In order to include DfD into the environmental impact calculation, the Building Circularity Index of Alba Concepts is used. The assumption that the Building Circularity Index is directly related to the probability of a building being (partly) reused in the future is made. How this index is exactly incorporated is elaborated in section 4.4.

Reuse is not taken into account by default. Design for Deconstruction is an important concept to include in this thesis, so this has to be included. The formula in its current state only accounts for recycling in the production and end–of–life phase. Next step is to include reuse (and thus DfD) in these life cycle phases as well.
In section 4.3, the PEF equation will be taken apart such that it can be modified in order to include these concepts.

4.3 MODIFICATION OF THE PEF EQUATION

The goal of this part is to develop a new allocation method, which can include the the Design for Deconstruction concept at both the construction phase, as the end–of–life phase. section 4.2 introduced and selected all theoretical concepts and ideas needed to come up with a comprehensive method. This chapter continuous on that selection by modifying the chosen PEF equation.

First, the equation is modified in a general way in subsection 4.3.2, where general parameters for reuse are included. Then, the use of a donor structural framework (DfD at construction phase) and DfD at EoL phase is added to the equation separately in subsection 4.3.3. Hereafter, the different possible combinations of reuse are developed as scenarios in subsection 4.4.2 and the parameters for the model are stated in subsubsection 4.3.2.2. Finally, these developed scenarios are implemented in the parametric grasshopper script in subsubsection 4.4.2.1.

4.3.1 Separation of PEF equation

The *PEF* equation is separated into its different input and output life cycle phases, in order to see how the equation is built up and how it can be adapted to specific needs. This is done in Figure 4.5. For a explanation of all parameters of the equations, see Table 4.3.

$$\overbrace{\underbrace{\left(1-\frac{R_1}{2}\right)E_v}_{\text{A}} + \underbrace{\frac{R_1}{2}\cdot E_{recycled}}_{\text{B}}}^{\textbf{Input}} + \overbrace{\underbrace{\frac{R_2}{2}\left(E_{recycling,EoL} - E_v^* \cdot K\right)}_{\text{C}} + \underbrace{R_3\left(E_{ER} - LHV\begin{pmatrix} X_{ER,heat}\cdot E_{SE,heat} + \\ X_{ER,elec}\cdot S_{SE,elec}\end{pmatrix}\right)}_{\text{D}} + \underbrace{\left(1-\frac{R_2}{2}\right)E_D - \frac{R_1}{2}\cdot E_D^*}_{\text{E}}}^{\textbf{Output}}$$

Figure 4.5: *PEF* equation separated into input (A–B) and output (C–E) stages of a product life cycle

Block A — Input: Production of virgin material

$$\begin{aligned}&(1-\frac{1}{2}R_1)E_V \\ &= \text{(amount of virgin material)} \cdot \text{(impact virgin material)}\end{aligned} \tag{4.3}$$

- Only recycled material taken into account as avoidance of virgin impact. reuse not taken into account.

Block B — Input: Recycled content

$$\begin{aligned}&\frac{1}{2}R_1 E_{recycled} \\ &= \text{(amount of recycled material)} \cdot \text{(impact recycled material)}\end{aligned} \tag{4.4}$$

Block C — Output: Recycling at EoL –credits from avoided primary production

$$\begin{aligned}&\frac{1}{2}R_2(E_{recycling,EoL} - E_v^* \cdot K) \\ &= \text{(amount of recycled material at EoL)} \cdot \text{(impact recycled material at EoL)} \\ &- \text{(avoided burden of using recycled i.o. virgin material in next phase)} \\ &\cdot \text{(material quality ratio)}\end{aligned} \tag{4.5}$$

- K only takes the current and next material cycle into account, due to the 50/50 allocation method used in this formula. However, parameter [A] (Nicholson Loss–of–Quality (LoQ) formula in Figure 4.4b) takes all material cycles into account.

Block D — Output: Energy recovery

$$\begin{aligned}&R_3(E_{ER} - LHV \cdot X_{ER,heat} \cdot E_{SE,heat} - LHV \cdot X_{ER,elec} \cdot E_{SE,elec}) \\ &= \text{(amount of incinerated material at EoL)} \cdot \text{(impact of energy recovery} \\ &\text{process)} - \text{(avoided impact of substituted energy production)}\end{aligned} \tag{4.6}$$

Block E — Output: Disposal

$$\begin{aligned}&(1-\frac{1}{2}R_2 - R_3)E_D - \frac{1}{2}R_1 E_D^* \\ &= \text{(Material disposed)} \cdot \text{(impact of disposing)} \\ &- \text{(recycled content at EoL)} \\ &\cdot \text{(disposal impact avoided by using recycled material in next life cycle)}\end{aligned} \tag{4.7}$$

- Negative credits due to avoiding disposal emissions due to reusing materials is not taken into account.

4.3.2 Adding general reuse to PEF equation

4.3.2.1 *Modification of the equation*

As mentioned in subsection 4.2.4, the *PEF* method is a 50/50 allocation method. After a change of method was opted for multiple reasons (see subsection E.0.1), the original 50/50 method is being kept due to its easy–to–modify ability. In this section, the original *PEF* equation is modified in order to include reuse in a general manner.

The adaptation from the original to the new equation is schematized in Figure 4.6. As can be seen, the original equation is first adapted to include the general reuse component. After this, the incineration part of the equation is adapted in such a way that in can be combined with existing NMD data. Lastly, the factor of remaining service life is incorporated.

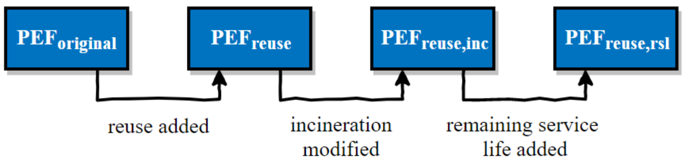


Figure 4.6: Modification of the original *PEF* equation to an equation with the required elements added

This latter part is not already included because it is assumed that materials can be recycled forever (the Technical Service Life (TSL) of a material is eternal). However, when structural elements are being reused, the TSL of the material does matter. Therefore, the factor between the length of the current life cycle and the remaining service life is taken into account. This concept is visualized in Figure 4.7.

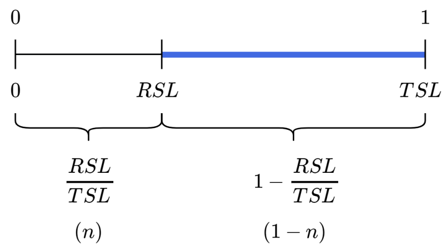


Figure 4.7: Derivation of the $(1 - n)$ factor, where the ratio between the Reference Service Life of a building and the Technical Service Life of a material is normalized from $[0 - TSL)$ to $[0 - 1)$.

Why and how all parts of Figure 4.6 are being executed, is elaborated in Appendix E. Only the final general equation is shown in Equation 4.8. The modifications due to all different requirements are marked with the different colored boxes. For further elaboration on all parameters in this equation, see Table 4.3.

$$
\begin{aligned}
PEF_{reuse,rsl} = \quad & \chi \Bigg[\left(1 - \frac{R_1}{2} - \boxed{\frac{R_4}{2}}\right) \boxed{E_v n_c} + \frac{R_1}{2} E_{recycled} \\
& + \boxed{\frac{R_4}{2} E_{reused}} + \frac{R_2}{2} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + \boxed{R_5 \left(\boxed{n} E_{reusing,EoL} - \boxed{(1-n) E_v^* K_{reu}}\right)} \\
& + \left(1 - \frac{R_2}{2} - R_3 - \boxed{(1-n) R_5}\right) \boxed{E_D n_c} \\
& + \boxed{R_3 \left(E_{ER} - LHV \left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right)} \\
& - \frac{R_1}{2} E_D^* - \boxed{\frac{R_4}{2} E_D^*} \Bigg]
\end{aligned}
\tag{4.8}
$$

with:

$$
\begin{aligned}
\chi &= \frac{m}{GFA \cdot RSL} \\
m &= \text{total mass of the material in the building} \\
GFA &= \text{Gross Floor Area of the building} \\
RSL &= \text{The functional service life of the building} \\
\boxed{eq.} &= \text{Added reuse component} \\
\boxed{eq.} &= \text{Modified incineration part} \\
\boxed{eq.} &= \text{Added Remaining Service Life component}
\end{aligned}
$$

4.3.2.2 *Equation parameters*

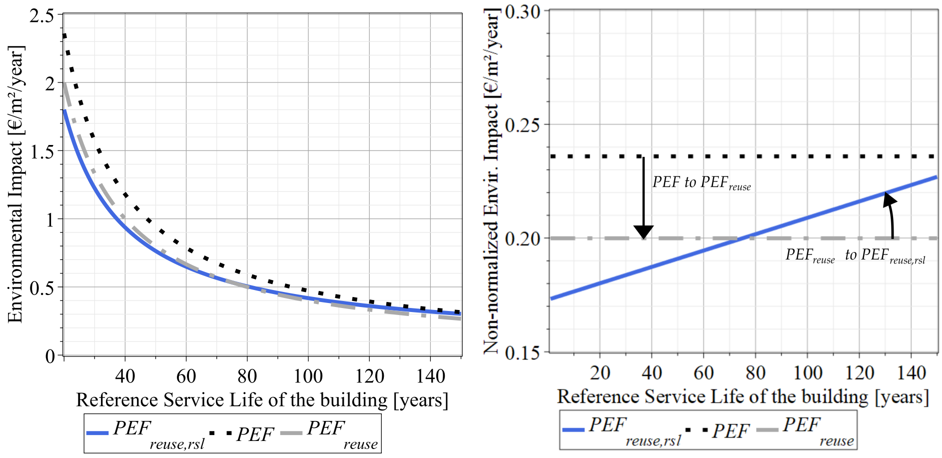
The different parameters of the developed allocation methods of Equation 4.8, 4.9 and 4.11 are summarized in Table 4.3. The table is divided into a section which parameters are derived from an LCA. The LCA calculates the environmental impact in euro per kg, which is elaborated in subsection 4.4.1. The argumentation of all these parameters is elaborated in Appendix F. The summarized input of those parameters can be found in the tables of Appendix G.

Parameter	Unit	Explanation
Life Cycle Assessment parameters		
Parameter	**Unit**	**Explanation**
E_v	€/ kg	Environmental impact of production virgin material.
$E_{recycled}$	€/ kg	Environmental impact of production recycled material.
E_{reused}	€/ kg	Environmental impact of modification reused material.
$E_{recycling,EoL}$	€/ kg	Environmental impact due to the recycling process at the EoL.
$E_{reusing,EoL}$	€/ kg	Environmental impact due to the reusing process at the EoL.
E_v^*	€/ kg	Environmental impact for the acquisition and pre–processing of virgin material assumed to be substituted.
E_{ER}	€/ kg	Environmental impact due to the Energy Recovery process.
$E_{SE,r}$	€/ kg	Avoided Renewable energy production environmental impact
$E_{SE,r}$	€/ kg	Avoided Fossil energy production environmental impact
E_D	€/ kg	Environmental impact due to the disposal of waste material.
E_D^*	€/ kg	Environmental impact for the disposal of waste material at the EoL of the material from which the recycled content is derived.
Other parameters		
Parameter	**Unit**	**Explanation**
RSL	year	Reference Service Life of the building
TSL	year	Technical Service Life of the construction material.
m	kg	Mass
GFA	m^2	Gross Floor Area
R_1	%	Recycling rate (input)
R_2	%	Recycled content (output)
R_3	%	Incineration content (output)
R_4	%	Reuse rate (input)
R_5	%	Reused content (output)
R_r	%	Percentage of the total energy produced in the Netherlands coming from renewable resources.
R_f	%	Percentage of the total energy produced in the Netherlands coming from fossil resources.
K_{rec}	-	Ratio for difference in quality between first and secondary material after recycling.
K_{reu}	-	Ratio for difference in quality between first and secondary material after reusing.
P_{r4}	%	Percentage of the load–bearing structure that is constructed out of reused elements.
P_{r5}	%	Percentage of the load–bearing structure that is being reused in the future.
BCI	-	Building Circularity Index
LHV	Mj/kg	Lower Heating Value of the incinerated material.

Table 4.3: Equation parameters to be known, split into parameters which are derived using an LCA and parameters which are derived from literature and directly implemented in the scenarios.

4.3.2.3 *Validation of the modified equation with the original PEF equation*

To sum it up, the results of all modification steps are shown in Figure 4.8, with the final equation in blue, $PEF_{reuse,rsl}$. In this case, the modified equation starts at a lower impact, but gradually approaches the original equation, due to the reuse not being able at the end of the material Technical Service Life.



(a) Equations including χ

(b) Non-normalized equations (divided by χ)

Figure 4.8: Comparison of the modified equations with the original PEF equation.

The process of modifying the original equation is best to be seen in the non–normalized equations of Figure 4.8b. This graph shows the environmental impact for the allocation equation only, thus without including $\chi = \frac{m}{RSL \cdot GFA}$. As can be seen, the step from the original PEF equation to PEF_{reuse} lowers the environmental impact for the same magnitude for every service life. $PEF_{reuse,RSL}$ changes the previous one by taking the remaining service life into account. As expected, this lowers the impact even further at a short service life (long technical service life of the material left), but reduces the impact of reuse at a longer service life (only short technical service life left). This is exactly the purpose of this modification.

4.3.3 Adding the use of a donor framework and future DfD to PEF equation

As mentioned at the start of this chapter, one of the main goals of this research is to include the DfD concept in existing LCA methodology. Until now, an existing methodology has been selected which is modifiable (PEF), whereafter it has been modified to include reuse percentages in general. Now, this modified equation is further modified in two separate ways. As mentioned before, DfD can be split into two ways:

1. Reuse at construction phase, which can be seen as the use of a Donor Structural Framework. Shortly, use the previous building to construct the current building.

2. Reuse at End–of–Life phase, which can be seen as the probability that the current building is being used to construct the next building in the future.

These different situations are schematized based on the life cycle phases of a building in Figure 4.9.

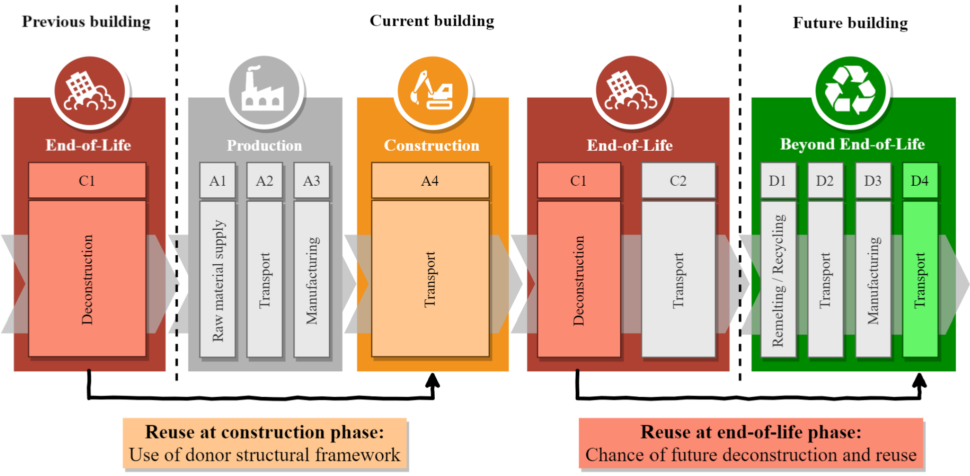


Figure 4.9: Difference in reuse at construction and end–of–life phase, corresponding with subsubsection 4.3.3.1 and subsubsection 4.3.3.2 respectively.

4.3.3.1 *Add the use of a donor structural framework*

Equation 4.9 shows the modified PEF equation of Equation 4.8, which now includes the option to use a donor structural framework. Figure 4.5 separated the original equation into an input and output phase. In order to include the donor framework into this methodology, the only modification needed is swapping the general reuse percentage (R_4) with a percentage of reused elements in case a donor structural framework is used (P_{r4}). Alongside, the standard recycling rate (R_1) is modified such that it is only taken from the non–reused part. These modifications are shown in Equation 4.9 as the blue boxed parts. For a explanation of all parameters of the equations, see Table 4.3. A validation of this equation in comparison to the original PEF equation can be found in subsubsection E.1.2.1.

$$
\begin{aligned}
E_{Donor} = \quad & \chi \Bigg[\left(1 - \boxed{\frac{R_1(1-P_{r4})}{2}} - \boxed{\frac{P_{r4}}{2}} \right) E_v n_c \\
& + \boxed{\frac{R_1(1-Pr4)}{2}} E_{recycled} + \boxed{\frac{P_{r4}}{2}} E_{reused} \\
& + \frac{R_2}{2} \left(E_{recycling,EoL} - E_v^* K_{rec} \right) \\
& + R_5 \left(n E_{reusing,EoL} - (1-n) E_v^* K_{reu} \right) \\
& + \left(1 - \frac{R_2}{2} - R_3 - (1-n) R_5 \right) E_D n_c \\
& + R_3 \left(E_{ER} - LHV \left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f} \right) \right) \\
& - \frac{R_1}{2} E_D^* - \frac{R_4}{2} E_D^* \Bigg]
\end{aligned}
\tag{4.9}
$$

With:

$\boxed{eq.}$ = Modified part of equation

P_{r4} = Percentage of the load–bearing structure what is constructed out of reused elements. (% reuse at construction phase)

4.3.3.2 *Add the probability of future deconstruction and reuse*

For the second case, the output part of Equation 4.8 is modified further. To quantify how much the to be reused parts reduce the total environmental impact, the following parameters are introduced:

$$P_{R5} \cdot BCI = \text{percentage of the impact which is due to a possible future reuse of the building.} \tag{4.10}$$

With:

$P_{r5} =$ The percentage of the load bearing structure that is being reused in case of deconstruction in the future.

$BCI =$ The probability of the existing structure being reused as a donor structural framework in the future (see subsection 4.2.3).

The introduction of the above implemented in the end–of–life part of standard equation (Equation 4.8) results in Equation 4.11. The modified parts are once again highlighted in blue. For a explanation of all parameters of the equations, see Table 4.3. A validation of this equation in comparison to the original PEF equation can be found in subsubsection E.1.3.1.

$$\begin{aligned} E_{DfD,EoL} = \quad & \chi\Bigg[\left(1-\frac{R_1}{2}-\frac{R_4}{2}\right)E_v n_c+\frac{R_1}{2}E_{recycled}+\frac{R_4}{2}E_{reused} \\ & +\boxed{\frac{R_2(1-P_{r5}BCI)}{2}}\left(E_{recycling,EoL}-E_v^{*}K_{rec}\right) \\ & +\boxed{P_{r5}BCI}\left(nE_{reusing,EoL}-(1-n)E_v^{*}K_{reu}\right) \\ & +\Bigg(1-\boxed{\frac{R_2}{2}(1-P_{r5}BCI)}-\boxed{R_3(1-P_{r5}BCI)} \\ & -\boxed{(1-n)P_{r5}BCI}\Bigg)E_D n_c+\boxed{(1-P_{r5}BCI)R_3}\Big(E_{ER} \\ & -LHV\left(R_r\cdot E_{SE,r}+R_f\cdot E_{SE,f}\right)\Big)-\frac{R_1}{2}E_D^{*}-\frac{R_4}{2}E_D^{*}\Bigg] \end{aligned} \tag{4.11}$$

With:

$\boxed{eq.} =$ Modified part of equation

$1-P_{r5}BCI =$ Remaining part of the structure which is not reused at EoL.

4.3.4 Conclusions

Sub research–question 2c can be answered based on this section:

How should the existing allocation method be modified such that it includes the donor framework and DfD concept?

- The Product Environmental Footprint (PEF) method does include end–of–life allocation, but it does not include the Donor Structural Framework and Design for Deconstruction concept.
- Before the Donor Framework and DfD were added, three modifications were executed:
  1. General reuse was added
  2. Incineration part of the equation was modified in such a way that it fits the input from the NMD processes database.

3. A remaining service life factor was added.

- The use of a donor structural framework is added to the equation by switching the standard reuse percentages at the construction part with a project specific percentage of which the new building exists of donor material. The recycled content percentage is modified in accordance.
- The probability of future deconstruction and reuse (DfD) is added to the equation by adapting the reuse percentage at the end–of–life part such that it is the **probability** of the existing structure being reused times the **percentage** of the load–bearing structure that is actually being reused in that case.

4.4 LCA AND SCENARIO DEVELOPMENT

Now the modification of the equations is performed, the actual development of the Environmental Impact Calculation (EIC) as required in the tool can take place. As shown in Figure 4.10, the EIC consists of two main parts.

1. **Life Cycle Assessment**
   This part calculates the environmental impact for a certain life cycle phase for 1 kg of a certain material. For instance, the environmental impact in euros for the demolition and disposal of 1 kg C30/37 concrete (E_D). The distribution of impact between different life cycles of a building is not taken into account.
2. **End–of–Life allocation scenarios**
   This part calculates the final environmental impact based on the allocation equations of section 4.3. These equations have the results of the LCA as input.

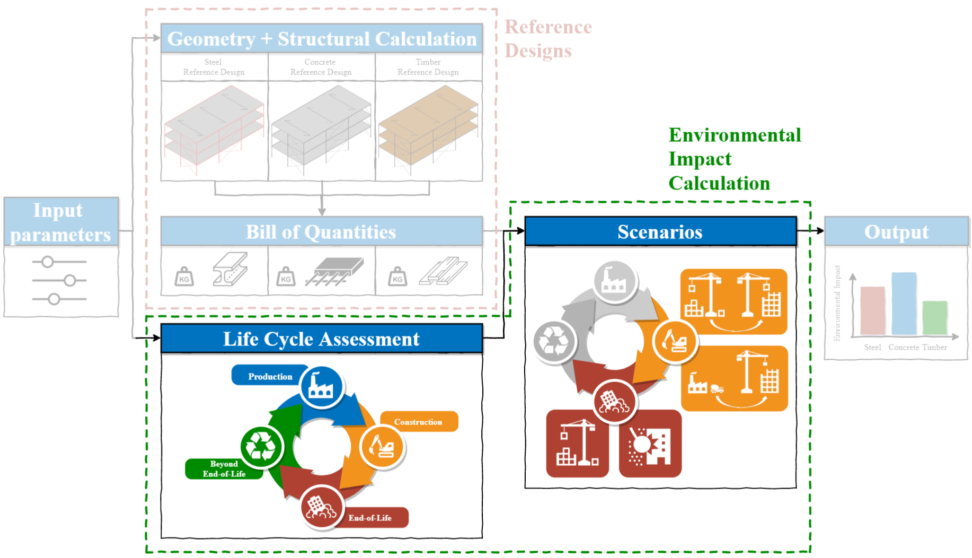


Figure 4.10: Place of the allocation scenarios in the parametric model.

Figure 4.11 shows the approach taken in this research as an adoption of the standard Dutch calculation rules from the "Determination Method of Environmental Impact of Buildings and Civil Works" from Stichting Bouwkwaliteit (SBK). The original approach can be found in the introduction of this thesis in Figure 1.1. In this research, the NIBE EPD app, which is a Life Cycle Inventory (LCI) database, is used as a basis on which an LCA of the total building is performed, based on the Product Category Rules of Figure 4.2.

The environmental impact LCI data of raw materials and building elements in the NIBE database are provided by specialists who have performed life cycle assessment studies and provided Environmental Product Declaration (EPD)s of these materials and elements, i.e. have documented what quantities of inputs (raw materials, energy, processes) and outputs (emissions to environment) are involved during the respective service life stages. The database comprising these LCI data of construction materials and processes is therefore also the limiting factor for estimating the environmental impact of constructions, as LCI data for only a limited number of (raw) materials, elements and (transport) processes are as yet available [Jonkers, 2020]. The remaining data, in Figure 4.11 shown as "Missing LCA data" is further gathered from other research, elaborated in Appendix F.

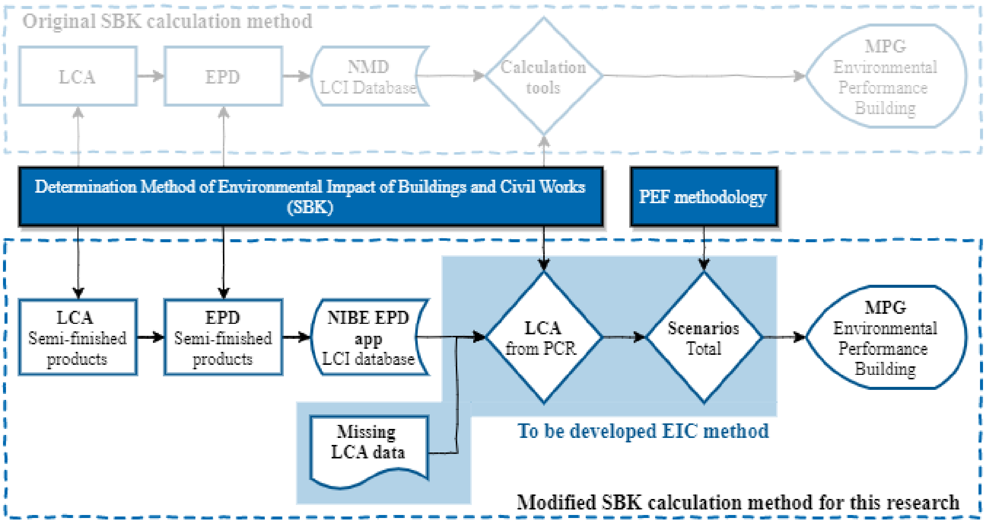


Figure 4.11: Place of the to be developed Environmental Impact Calculation, in comparison with the original SBK method, as shown and elaborated in Figure 1.1. The developed Environmental Impact Calculation EIC of this chapter is shown in the blue surface.

4.4.1 Life Cycle Assessment

As mentioned earlier, the Life Cycle Assessment calculates the environmental impact per life cycle phase for 1 kg of the relevant material. The following phases cycle activities are distinguished:

- Production of virgin material (A1 — A3)
- Recycling of material (D1)
- Demolition of the building (C1)
- Deconstruction of the building (C1)
- Disposal of the material (C4)
- Incineration and energy recovery of timber (C3)
- Possible transport types (A2/A4/C2/D2/D4)
- Transport distances per life cycle phase (A2/A4/C2/D2/D4)

For each material apparent in the model, the environmental impact is calculated per life cycle activity (A1, A2, C1, D3 etcetera). The results of these calculations are shown in Appendix G. These life cycle activities are used in order to calculate the environmental impact of a certain life cycle phase (E_{virgin}, E_{reused}, $E_{disposal}$ etcetera), as elaborated in Appendix F. The considered different life cycle phases for steel are shown in Figure 4.12. This includes the virgin material, recycling, reusing and disposal impact. The corresponding life cycle phases of concrete and timber are given in subsection I.2.2 and I.2.3 accordingly.

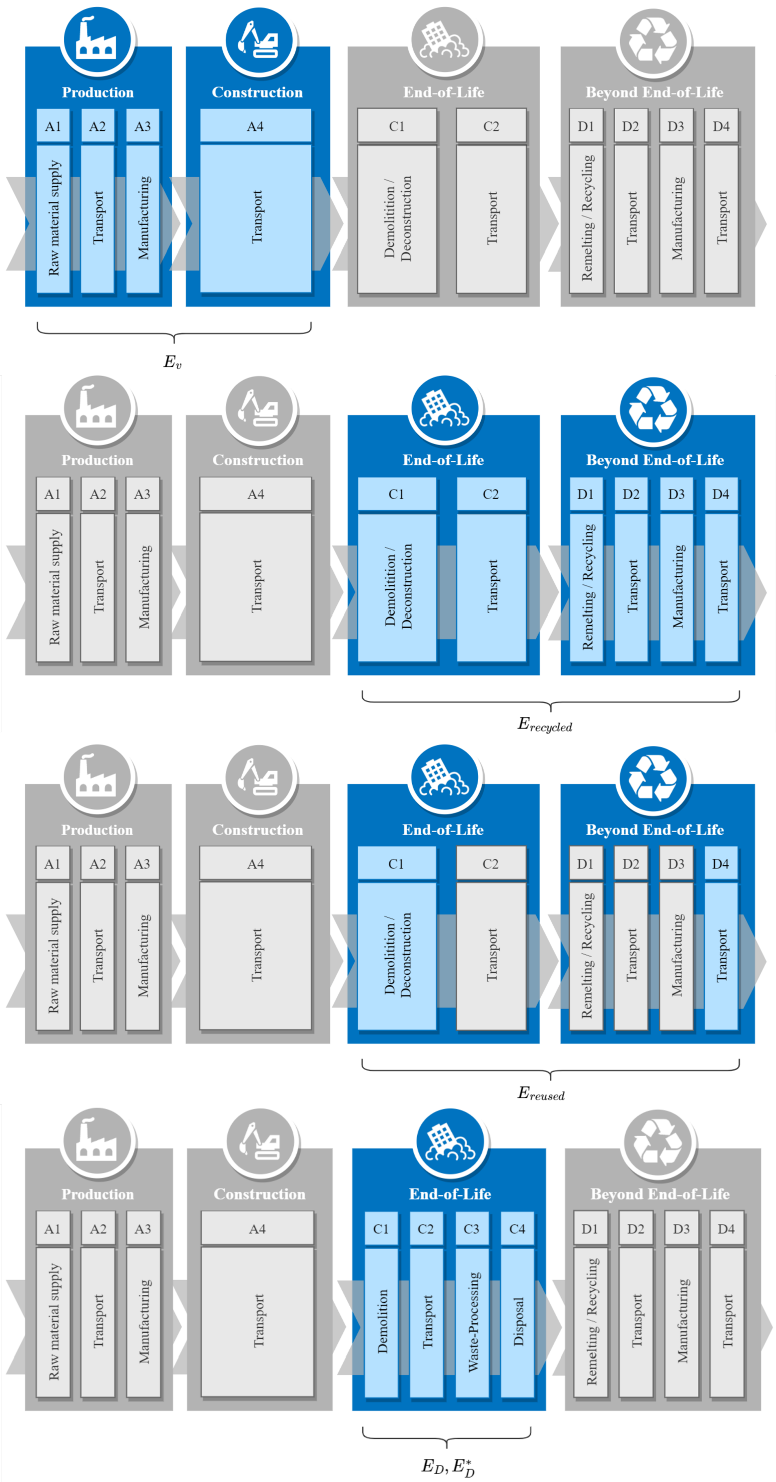


Figure 4.12: To be considered LCA stages for the different material impact life cycle stages of steel. From top to bottom: Virgin impact (E_v), recycling impact ($E_{recycled}$), reusing impact (E_{reused}) and disposal impact (E_D).

4.4.1.1 *LCA grasshopper input*

The LCA is modeled in Grasshopper per material and per life cycle phase. This can be seen as a matrix with the columns being the different life cycle phases and the rows being the different materials. Every cell then represents the combination of a certain row (material) and column (life cycle phase). This setup is shown in Table 4.4.

	E_v / E_v^*	$E_{recycled}$	E_{reused}	E_D / E_D^*	E_{ER}	E_{SE}
Structural steel (S355)						
Hollow-core slab						
Concrete (C30/37)						
Reinforcement						
Glued Laminated Timber						
Insulation (Rockwool)						
Ghypsum						

Table 4.4: LCA grasshopper input matrix. Every cell corresponds to a combination of its row and column element. The result in grasshopper is shown in Figure H.12.

4.4.2 Scenario development in order to combine all model options

In principle, all separate EoL allocation equations are now established, namely:

- An allocation equation which takes reuse into account in a fast and straightforward way, for early decision making (Equation 4.8). This can be considered as the 'average' equation.
- An allocation equation which takes into account a donor structural framework is used in order to reuse structural elements (Equation 4.9).
- An allocation equation which takes the probability that a building's structural components are being reused as a donor structural framework in the future into account (Equation 4.11).

As shown in Figure 4.9, the impact can be split in an part coming from the phase the building is being built (construction) and a part coming from the phase the building is demolished/deconstructed (EoL). Different options for these phases can be chosen, and their combinations form the following six allocation scenarios:

1. A quick-and-dirty calculation: Used in earliest design phase when few decisions have been made regarding the design and therefore the least amount of information is known.
   Equation 4.8 is used with mean parameters, only average values for reuse at construction or end–of–life phase are taken into account.
2. Calculation of the impact when a donor structural framework is used at construction phase, but no specific calculations for the probability of DfD at the end–of–life are required.
   Equation 4.9 is used, with P_{r5} included as a project specific percentage. The resulting equation can be found in subsection E.1.2.
3. Calculation of the impact when the probability of DfD at the end–of–life phase of a building is included, but no information regarding the use of a donor framework in the construction phase is at hand.
   Equation 4.11 is used in this case.
4. Calculation of the impact when both a donor structural framework is used at construction phase and the probability of DfD at the end–of–life phase needs to be included.

This equation combines the input (construction) part of Equation 4.9 and the output (EoL) part of Equation 4.11. The resulting equation can be found in subsection E.1.4.

5. Calculation when it is certain no donor structural framework is used at the construction phase and no specific calculation for the probability of DfD at the EoL are required.
   This equation erases all reuse parts at the construction phase and combines this with the EoL part of Equation 4.8. The resulting equation can be found in subsection E.1.5.

6. Calculation when it is certain no donor structural framework is used at the construction phase, but the probability of DfD at the EoL phase of a building needs to be included.
   This equation erases all reuse parts at construction phase and combines this with the EoL part of Equation 4.11. The resulting equation can be found in subsection E.1.6.

While scenario 1 — 3 straightforwardly use Equation 4.8, 4.9 and 4.11, the composition of the remaining scenario equations are elaborated in section E.1.

4.4.2.1 *Scenario grasshopper input*

The six aforementioned end–of–life allocation equation scenarios are implemented in the grasshopper script in the following manner: Initially, the different input parameters as shown in Table 4.5 are imported from Excel, which script is visualized in Figure H.20. The development of these parameters is elaborated in Appendix F. Then, the results of the Life Cycle Assessment from subsubsection 4.4.1.1, the environmental impact factors (E_v, $E_{recycled}$, E_{reused}, E_D, E_{ER}, $E_{SE,r}$ and $E_{SE,f}$), are summarized per material in Figure H.21. Subsequently, the impact factors and the input parameters are combined in the end–of–life equations. These equations iterate over a lifespan of 150 years, calculating the environmental impact of a specific material for a specific scenario from a lifespan of 1 — 150 years.

After this, the results of all materials are summarized per scenario, such that the environmental impact for the total load–bearing structure is calculated, see Figure H.22. This procedure is executed for every scenario. Lastly, the environmental impact of all scenarios is exported to excel in order to visualize and compare the results, see Figure H.23.

Parameter	Material					
	Steel	Hollow-slab floor	In-situ cast concrete	Rebar	Timber	Insulation & Gypsum
R_1	0.51	0.02	0.02	0.53	0.12	0
R_2	0.91	0.8	0.8	0.95	0.1	0
R_3	0	0	0	0	0.8	0
R_4	0.04	0	0	0	0.06	0
R_5	0.08	0	0	0	0.05	0
R_r	0	0	0	0	0.09	0
R_f	0	0	0	0	0.91	0
P_{r4}	0.75	0.2	0.2	0.75	0.5	0
P_{r5}	0.75	0.2	0.2	0.75	0.5	0
p_s	0.32	0	0	0	0	0
K_{rec}	1	0.06	0.06	1	0.05	0
K_{reu}	0.8	0.8	0.8	0	0.5	0
LHV	0	0	0	0	13.99	0
BCI	0.76	0.21	0.21	0.21	0.60	0
n	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
n_c	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
m	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
GFA	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
RSL	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
TSL	150	150	150	150	75	30

Table 4.5: Input parameters for the scenarios implemented in the grasshopper script, which is elaborated in Appendix F.

4.4.3 Conclusions

This section has answered sub–research question 2b:

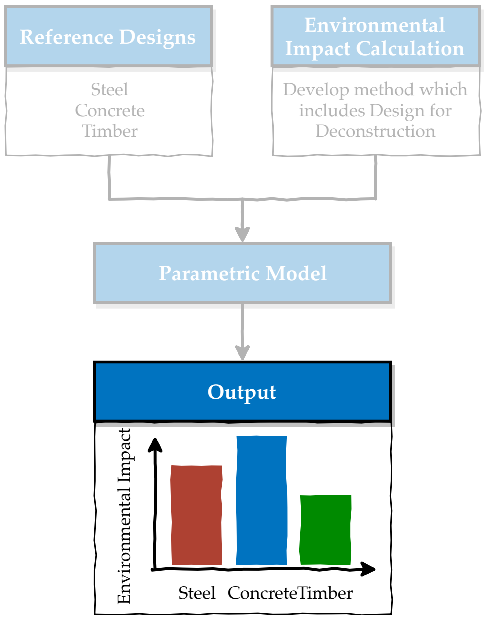
How can the newly established methodology be implemented in a parametric model?

The parametric script splits the Environmental Impact Calculation (EIC) into two parts:

1. The Life Cycle Assessment (LCA) which calculates the impact of all processes involved per life cycle per kg material.
2. The 6 Scenarios calculate how every process of every life cycle of the LCA is weighted in the total environmental impact calculation. This is the so–called end–of–life allocation. Every EoL scenario calculates a different combination of use of a donor framework, no use of a donor framework, DfD or no DfD.

Part III

Results and Final Remarks



This part concludes the research. First, the early results of the tool are benchmarked and the model is corrected according to those benchmarks. Then, the final results are described and discussed, whereafter general conclusions are drawn and the main research question is answered. At last, recommendations for further research are opted.

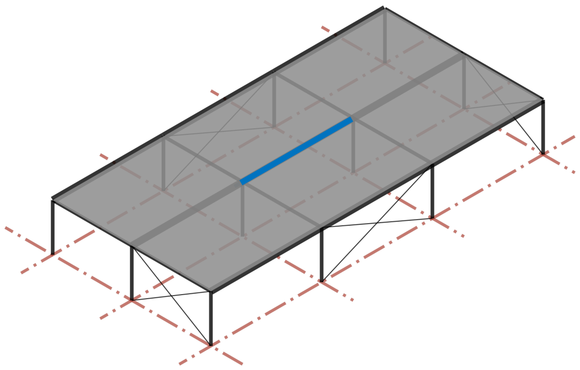
5 BENCHMARKING OF THE PARAMETRIC MODEL

This chapter covers the benchmarking of the structural calculations and the environmental impact calculations. First, the structural calculation principles and results in grasshopper are validated with MatrixFrame in section 5.1. These results are implemented in the parametric model. Then, the general results of the environmental impact calculation are validated in section 5.2. Only scenario 1 (average values) is used here; this scenario is closest to the standard Environmental Impact Calculation (EIC) of MPGcalc.

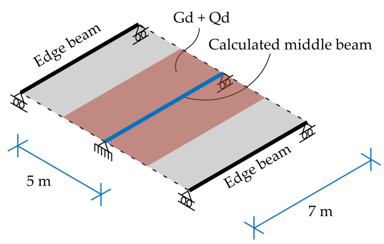
5.1 STRUCTURAL CALCULATIONS

5.1.1 Considered member

Figure 5.1a shows the middle floor of the reference design, of which the middle beam is chosen for validation. The beams are loaded in bending, which is generally the limiting factor for structures with larger spans, due to their deflection requirement. For this reason, only the beams are validated. The middle beam is chosen as this one has the highest load, which is is shown in Figure 5.1b. It is recommended to further validate the structural principles when using the parametric model. All connections are assumed hinged due to the Design for Deconstruction (DfD) concept applied in this study, which assumes easy to deconstruct frameworks. By assuming every connection hinged, the middle beam can be schematized as a simply supported beam, shown in Figure 5.1b.



(a) Middle floor of the reference design, with the validated middle beam shown in blue.



(b) Schematization of the loads and surface applied in the structural calculation of Figure I.1, shown in red.

Figure 5.1: schematization of the mechanics, as applied in the validation.

Only steel and timber beams are validated. Generally, concrete beams are already dimensioned based on rules of thumb, after which the reinforcement is calculated accordingly. Because this study is already based on existing rules of thumb for concrete beams, it is considered less crucial to validate them. However, it is recommended to validate this in a later stadium when the parametric model is actually used. The validation of the steel and timber beams are shown in section I.1. Only the conclusions of the validation are shown here.

5.1.2 Conclusion

Steel beam

The steel beam fulfills the unity check on strength being lower than 1.0. A unity check of 0.42 is low, but can be expected in the early design phase calculations. Significant gains can be achieved by optimizing the design.

$$u.c. = \frac{\sigma_{hh}}{f_y} = \frac{150}{335} = 0.42 \tag{5.1}$$

Timber beam

The original rule of thumb for glued laminated beams of $\frac{h}{l} = \frac{1}{20}$ does not meet the strength requirement. Therefore, the rule of thumb is modified to $\frac{h}{l} = \frac{1}{10}$. A maximum stress of 18 N/mm^2 is reached which results in the following unity check.

$$u.c. = \frac{\sigma_{hh}}{f_{m,k} \cdot k_{mod}} = \frac{18}{28 \cdot 0.9} = 0.71 \tag{5.2}$$

This unity check is similar to the unity check from the corresponding steel beam of Figure I.2. For this reason, the modified rule of thumb is applied in the parametric model.

Note: The modified Rule of Thumb is not standard nor extensively validated.

5.2 ENVIRONMENTAL IMPACT CALCULATIONS

5.2.1 Plan

This section considers the benchmarking of the first results of the parametric tool regarding the environmental impact. This is done based on the results of scenario 1 with a functional service life of 50 years, the standard service life of office buildings.

Figure 5.2: Environmental impact of the average equation (Scenario 1), which are validated in section 5.2.

The Bill of Materials (BoM) following from the parametric model with the case study dimensions are entered in MPGcalc. MPGcalc is a free–to–use environmental cost calculation application used in the Netherlands. The outcomes of MPGcalc are compared with the outcomes of scenario 1 from the parametric model. These outcomes should be comparable. Only the results of the validation are presented in this section. Further information can be found in section I.2.

5.2.2 Result comparison steel design

The steel material in MPGcalc has an environmental burden which is 60% lower than the model, see Figure 5.3. This is due to the fact that MPGcalc uses Nationale MilieuDatabase (NMD) values for steel, which, as can be read earlier in this study, are unrealistic with regard to their recycling percentage and thereof their impact. The conclusion that can be drawn is that there is a significant difference in impact between these two calculation methods; the model uses a more realistic approach. The hollow–core slabs values do agree fairly well, which is to be expected.

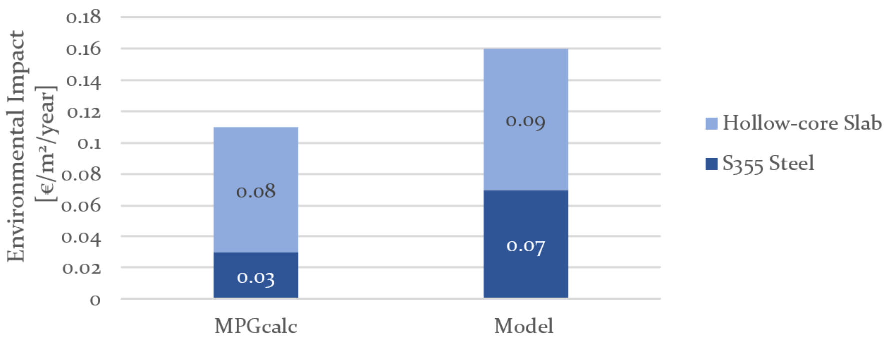


Figure 5.3: Comparison of the MPGcalc vs. Developed model environmental impact of the steel design.

5.2.3 Result comparison concrete design

Both values of the reinforced concrete framework as the hollow–core slabs are similar. The total impact of the model is 15% higher than its MPGcalc equivalent, but this is considered too small to be further evaluated.

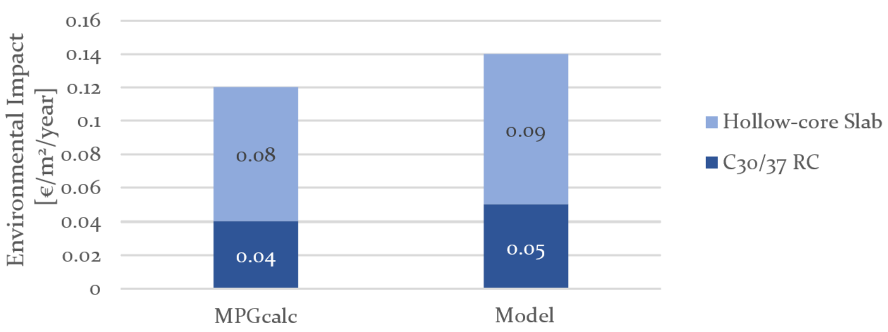


Figure 5.4: Comparison of the MPGcalc vs. Model environmental impact of the concrete design.

5.2.4 Result comparison timber design

The impact values of the timber design correspond the least of all designs. The glued laminated timber in MPGcalc has a 50% higher impact than the same material in the model. This is mainly due to the impact reduction from the incineration of wood. The model takes into account the incineration of wood at the end of its life cycle, for which a significant reduction in impact is gained. However, these values are not included in MPGcalc 1.2. The impact of the insulation does not match as well, but this is due to the fact that no thickness of the material can be entered in MPGcalc, so these materials do not correspond with each other.

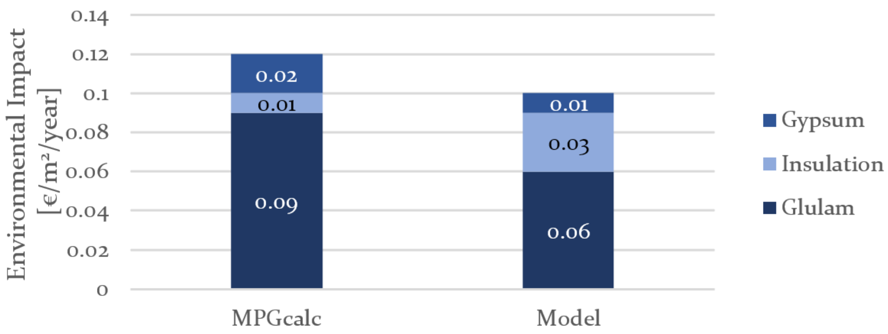


Figure 5.5: Comparison of the MPGcalc vs. Model environmental impact of the timber design.

5.3 CONCLUSION

As the model is now validated for both the structural part as the environmental impact part, final results can be exported from the model. However, for further use of this model it is recommended to further validate the model. Specifically the structural system and the timber environmental impact are recommended to be further validated.

6 RESULTS

This chapter shows the result of the case–study implemented in the parametric model and gives a quantitative answer to the main research question. This answer is evaluated and qualified in the discussion (chapter 7) and conclusion (chapter 8). The results represent the environmental impact of a certain design and scenario, which are specified in section 3.1 and subsection 4.4.2 respectively.

6.1 PARAMETRIC MODEL

In order to make an environmental impact calculation possible in the early design phase, a parametric model has been built. The result of the total model is shown in Figure 6.1. Every part of this model is separated and elaborated in Appendix H.

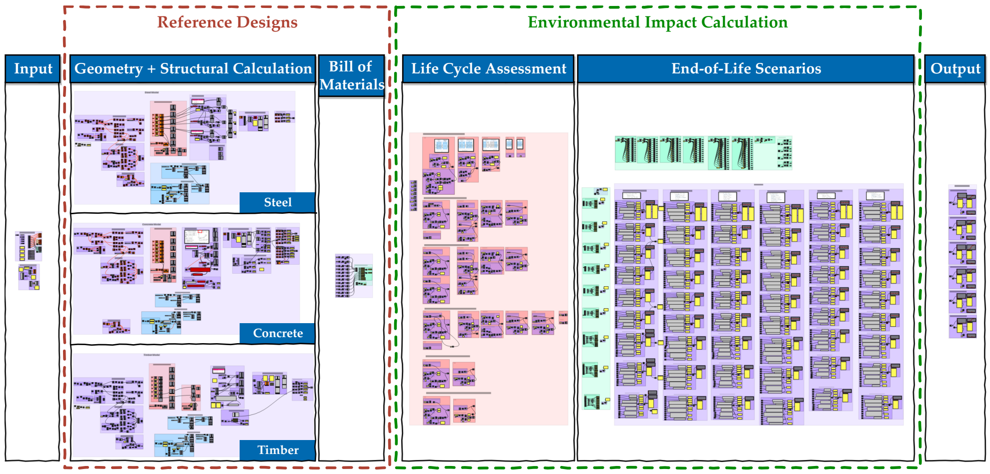


Figure 6.1: Total parametric model, as constructed to calculate the environmental impact in the early design phase.

Every reference design (accentuated in red in Figure 6.1) consists of two main parts, a build up of the geometry (which is approximately the same for each material) and a structural calculation (which differs for each material). The Bill of Materials is calculated which sums up the Reference Designs part.

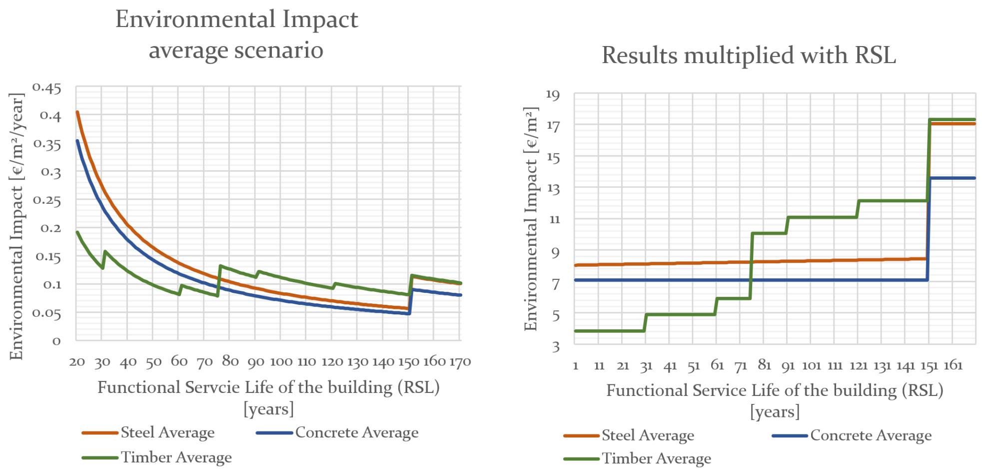
Then, the green outlined part, the Environmental Impact Calculation, assesses the aforementioned reference designs based on their sustainability score. This is done through an elaborate Life Cycle Assessment in combination with the End–of–Life scenarios, which are described in section 4.4. The results of these scenarios are clarified in the next sections.

6.2 ENVIRONMENTAL IMPACT CALCULATION

6.2.1 Environmental impact of the standard scenario

Figure 6.2 shows the results of scenario 1: Average (Equation 4.8). This scenario signifies the standard environmental impact calculation which mostly resembles the standard calculation method of MPGcalc and other existing tools. The only difference is that scenario 1 includes an average reuse percentage in the calculation, where the MPGcalc method does not.

Figure 6.2a represents the actual environmental impact of this scenario in [$€/m^2/year$]. These graphs are hard to compare, due to the fact that they are normalized (divided by) the service life of the building. In order to easily compare the difference in environmental impact, these results are multiplied by their corresponding service life (the number on the horizontal axis). This results in the unit [$€/m^2$].



(a) Environmental impact of the standard scenario.

(b) Results of Figure 6.2a multiplied with the designed service life of the building (RSL).

Figure 6.2: Environmental impact of the case–study with calculation option scenario 1: Average. Used as a quick–and–dirty calculation in early design phase.

Figure 6.2b shows that when no donor structural framework is used and the probability of reuse in the future is not taken into account, the environmental impact of the timber structure is lowest until a service life of 75 years. After 75 years, the impact of the timber structure shoots up and results in the highest environmental impact of all considered designs. Moreover, the timber structure discretely increases at 30 and 75 year intervals.

The steel design in Figure 6.2b has a higher environmental impact throughout the service life of the material of 150 years and it slightly increases continually. After 150 years, a major sudden increase is observed, which results in a similar environmental impact as the timber design.

In contrast to the concrete design, which has a constant multiplied environmental impact of 7 $€/m^2$ throughout its service life. This means that the concrete design has the least amount of impact when it is used for more than 75 years, but has the intermediate environmental impact when it is used less than 75 years. After 150 years, a major sudden increase is observed at the concrete as well, but this still results in the lowest overall environmental impact of all designs considered.

6.2.2 Environmental impact when a donor structural framework is used

When the impact of the use of a donor structural framework is considered, the results change considerably. In Figure 6.3 the results of this option in the parametric model is chosen and compared with the results of Figure 6.2b. In general, a clear decrease in environmental impact can be seen, but to which extend differs per material.

It is remarkable that the environmental impact of each material is evenly reduced over the life of the material. However, the factor that reduces the impact depends on the material. Turnover points in terms of the environmental impact of the different designs are indicated with a data label at the relevant lifespan.

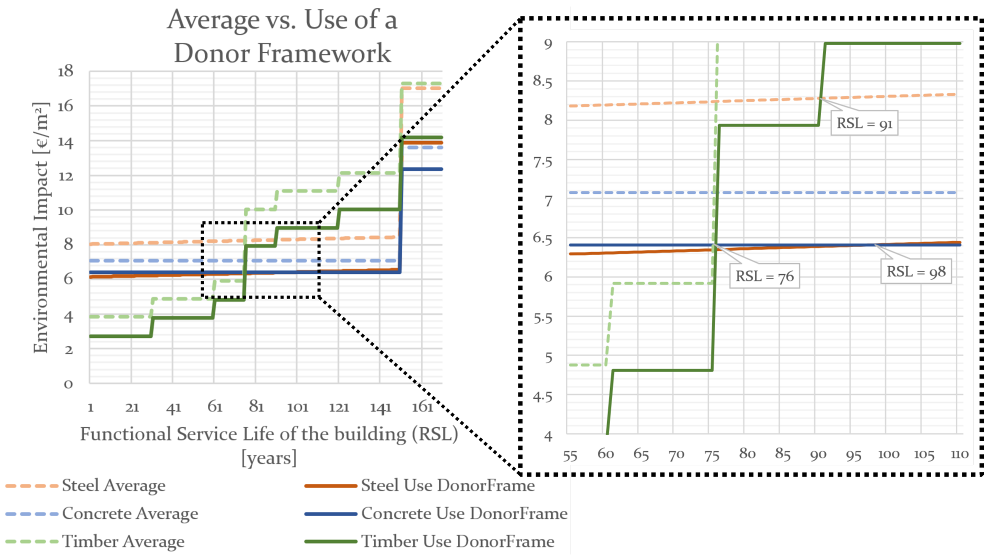


Figure 6.3: Environmental impact multiplied with its corresponding service life when a donor structural framework is used vs. the standard approach. The most important part of the graph is clarified with shown bigger.

Steel
Figure 6.3 shows that the impact of the steel design has been uniformly reduced over the lifespan of the building. When the lifespan is between 76 and 98 years, a steel design with a donor framework is the most sustainable solution of all donor framework designs. Moreover, it is never the least sustainable solution.

Figure 6.4 shows a decrease of 23 percent when using a donor structural framework. This applies to a design in which 75 percent of the steel construction and 20 percent of the hollow–slab floors consist of reused elements.

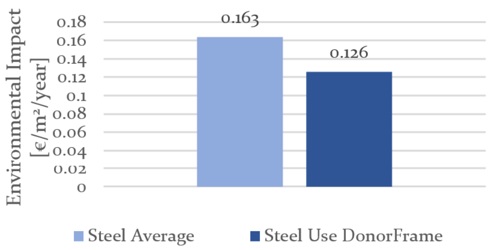


Figure 6.4: Environmental impact of the steel design when a donor structural framework is used for a service life of 50 years.

Concrete
Just like the steel design, the concrete design also shows a clear decrease in environmental impact by percentage over the entire lifespan of the building. It can be seen from Figure 6.5 that this decrease is around 10 percent. This decrease is achieved by using a donor concrete percentage of 20 percent for both the framework and the floors.

It can be seen from Figure 6.3 that the use of a donor framework for the steel design or the concrete design results in a similar environmental burden. The concrete design becomes a little more cost-effective as it lasts longer, with the turnover point at a service life of 98 years.

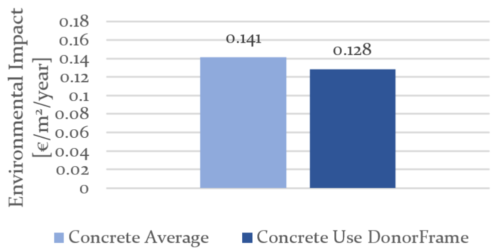


Figure 6.5: Environmental impact of the concrete design when a donor structural framework is used for a service life of 50 years.

Timber
When looking at Figure 6.3, the timber model with the donor framework has the lowest environmental impact of all designs considered, up to 76 years, just as observed for the average scenario in Figure 6.2. Even the timber design without the use of a donor framework has a lower environmental impact than the steel or concrete design with a donor framework. From 76 years onward, the environmental impact of the timber design rises above the other designs when the use of a donor framework is considered. Only the average steel scenario has a higher environmental impact beyond a service life of 76 years. After 91 years the timber design with donor framework creates a higher impact than the average steel scenario.

The timber model has a significantly lower environmental impact than the other designs at RSL = 50 years, the standard service life of an office, as shown in Figure I.17.

For now, the timber design environmental impact decreases by 25 percent when half of the load–bearing structure is constructed from donor structural elements, see Figure 6.6. Sound proofing materials are not recycled nor reused.

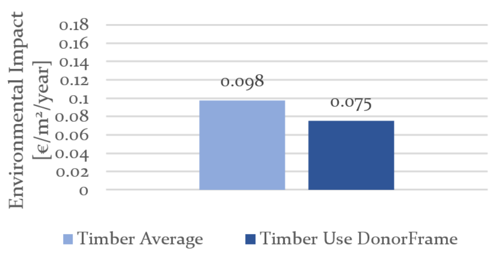


Figure 6.6: Environmental impact of the concrete design when a donor structural framework is used for a service life of 50 years.

6.2.3 Environmental impact when the probability of future reuse is considered

6.2.3.1 *Standard circularity (average BCI)*

When considering the Design for Deconstruction (DfD) aspect of the research, the results change again. In Figure 6.7 the results of the option when future remountability of the designs is considered are shown. These results are compared with the results of Figure 6.2. Note: This scenario takes the probability of future reuse into account, but assumes standard circularity. This means the actual Design for Deconstruction concept is not applied here. This concept is applied in subsubsection 6.2.3.2.

The general trend is a reduction of the environmental impact at relatively short lifetimes. When the lifetime of the building gets longer, the remountable scenario creates a higher impact than the standard scenario. Until a service life of 75 years, the timber design is the best option. After 75 years, the concrete design is the most sustainable option.

Steel has the highest impact of all designs between a lifespan of 7 and 75 years and after 150 years. For the building that has been in use for less than 7 years, concrete is the least sustainable solution, while after 75 years the wooden design is the least sustainable solution.

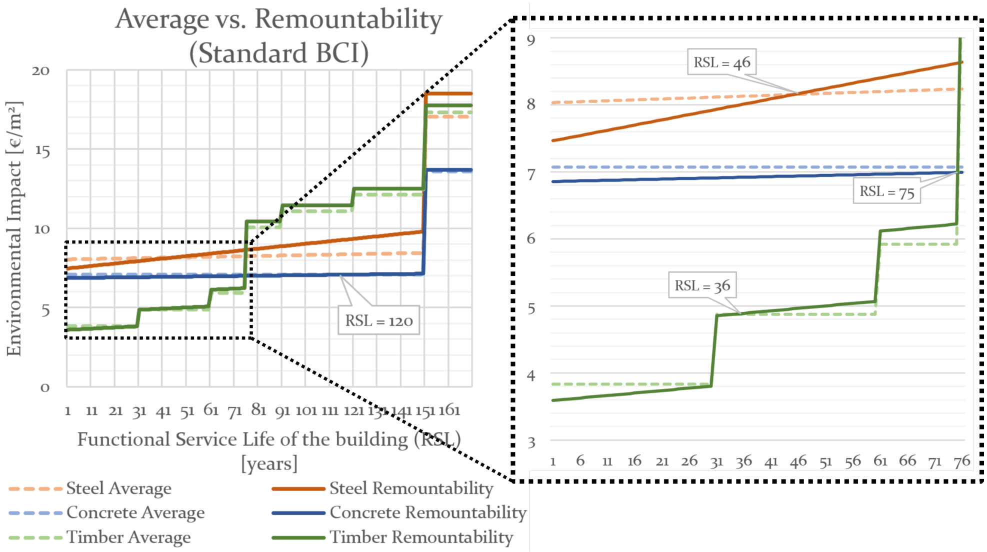


Figure 6.7: Environmental impact when the probability of future deconstruction and reuse is included (Remountability) vs. the standard approach. In this case, standard remountability is included, which results in an average Building Circularity Index per material.

Steel
Looking at the red lines in Figure 6.7, up to a buildings service life of 72 years, the steel design that includes disassembly is more sustainable than a design that does not include dissassembly (average scenario). After 72 years this ratio turns around. The "steel remountable" scenario therefore starts lower than the "steel average" scenario but gradually increases at a faster rated.

Concrete
When DfD is taken into account with a concrete design (blue lines), this hardly reduces its environmental impact, as can be seen in Figure 6.7. Up to a lifespan of 120 years, the impact of demountability has a positive influence on the environmental burden, but after that, the average scenario is the more sustainable approach. Strik-

ing is that for buildings that have a lifespan of more than 75 years, a concrete design is the most sustainable solution.

Timber

When comparing the timber DfD scenario with the average scenario (green lines), a number of things stand out. Up to a lifespan of 36 years, the DfD scenario gives a lower environmental burden than the average scenario. However, because the remountable scenario not only increases step–by–step in 30-year increments, but also gradually, this method gives an increasingly higher environmental burden after 36 years in comparison with the average scenario. It is striking that up to 75 years the line increases gradually and in steps, but after 75 years it only increases gradually.

6.2.3.2 *Highly remountable design (Design for Deconstruction applied)*

In Figure 6.8, the probability of future reuse is included in both models, except the for 'standard remountable' lines, a standard level of circularity (standard Building Circularity Index (BCI)) for each material is selected. On the other hand, 'max remountable' shows the environmental impact when an exceptionally high level of remountability is included (high BCI), which represents that the Design for Deconstruction concept is applied during the design phase of the building. This is applied by using a higher Building Circularity Index for every material than standard is assumed. The colored surfaces represent the lowest environmental impact of a certain material at a certain time span.

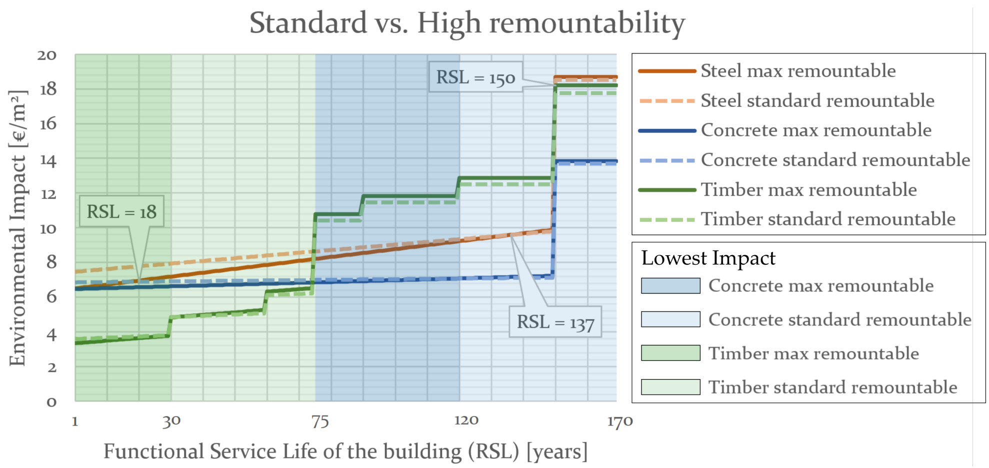


Figure 6.8: Environmental impact of a Structure with standard remountability vs. a highly remountable structure. Colored surfaces represent the corresponding lowest environmental impact at a certain time span.

Steel

Applying the Design for Deconstruction concept in a steel structural design, by applying both a fully remountable framework as concrete hollow–core slabs, results in the lowest environmental impact when a short building lifespan is estimated. Until a building service life of 18 years, this solution is more environmentally friendly than a standard concrete building. A highly remountable steel design has a lower environmental impact than a standard steel design until a lifespan of 137 years.

Concrete

A highly remountable concrete design only has a slightly less environmental impact than a standard concrete design. When a lifespan greater than 120 years is expected, the environmental impact of the highly remountable structure surpasses that of the standard concrete design.

Timber

The timber designs (shown in green in Figure 6.8), are quite similar. The turnover point between a standard timber building and a highly remountable building lies as early as 30 years. This means only for expected lifespans shorter than 30 years, the environmental impact of a remountable structure is lower than a standard structure.

6.2.4 Donor Framework and Design for Deconstruction compared

Figure 6.9 shows that using a donor structural framework always results in a lower environmental impact than applying the Design for Deconstruction concept by maximizing the remountability of a structure. Until a lifespan of 75 years, using a timber donor framework is the most sustainable solution. From 75 until 100 years this is the case for steel and from 100 years onward, a concrete design, whether or not using a donor framework, results in the lowest environmental impact.

Moreover, from a lifespan of 90 until 150 years, a DfD steel design has a similar environmental impact as a timber design where a donor framework is used. After 150 years, the steel DfD design becomes the least sustainable option.

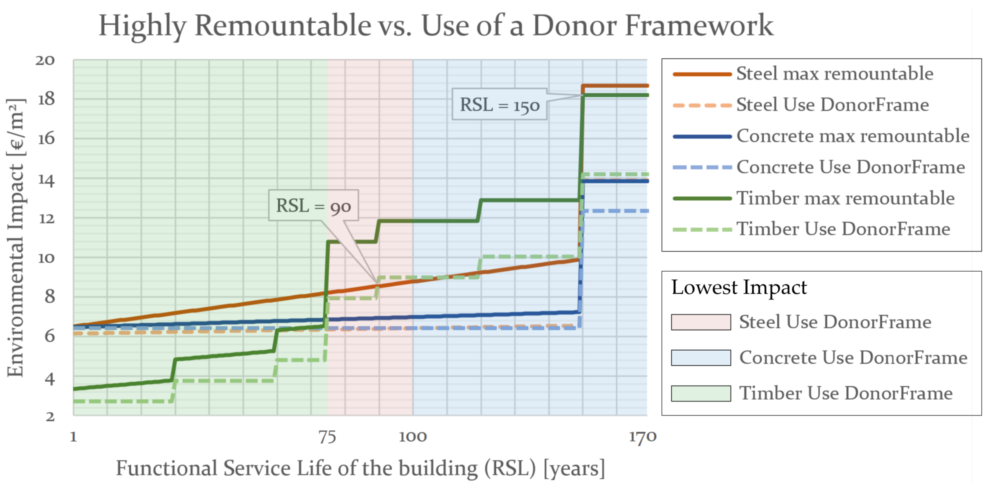


Figure 6.9: Environmental impact of a highly remountable structure vs. a structure where a donor structural framework is used.

6.2.5 Summarized results

In general, it can be observed that a timber design with a donor framework is the most sustainable solution up to a lifespan of 75 years, although all timber design solutions within this lifespan are more sustainable than their steel or concrete counterparts. From a lifespan of 75 to 100 years, a steel load–bearing structure with the use of a donor framework is the most sustainable solution and with a lifespan of more than 100 years, concrete is the most sustainable material.

7 DISCUSSION

This chapter analyses the obtained results and discusses the strengths and weaknesses of the created method. First, the general vision of the research is discussed, whereafter the functioning of the created framework and its flaws and strengths are reviewed. Then, the framework is split up into the parametric model and the environmental impact calculation, which are both discussed separately. Finally, in the reflection a birds-eye view on the research is taken and the main objective and research questions are addressed.

7.1 VISION

As mentioned in the problem definition of this research (section 1.3), there were a few problems which needed to be tackled. Firstly, little information was known about the actual environmental impact of Design for Deconstruction (DfD). This was partly due to the fact that the current Life Cycle Assessment (LCA) methodology was developed for the linear economy of yesterday, instead of the circular economy of tomorrow. The current LCA is calculated after the global design decisions were made, due to the extensive amount of information required to calculate the environmental impact. However, the early design phase is the phase where the basic design is developed and important design decisions are made. Decisions that should also be based on the result they have on the environmental impact of a building, which is not done this way until now.

Therefore, the aim of this research is to be able to choose the preferred construction material in the early design phase based on sustainability and including the donor framework and remountability. Because the calculation is made in the early design phase, there is great uncertainty in input parameters. The following vision has been developed to deal with this uncertainty and still be able to include the aforementioned concepts:

1. Develop a methodology with which the environmental impact can be calculated whenever a donor structural framework or a remountable structure is involved.
2. Construct a parametric model which consists of a structural calculation of a certain geometry and add the aforementioned methodology to the model, such that the model parametrically calculates the environmental impact of the considered geometry and materialization.

Combining the two parts results in a fully parametric environmental impact calculation which can be adjusted to every geometry as necessary. The reference designs in this research are chosen as general as possible such that the conclusions of the research are as generalizable as possible. However, conclusions regarding which construction material is most sustainable can differ between different designs. The model is built in such a way that the design can be adjusted as desired and the environmental impact calculation changes accordingly. This concept is vital for the use of this model in the early design phase.

The result of this method is the equivalent environmental costs per material and per scenario (use a Donor Framework [yes/no] and include Design for Deconstruction [yes/no]). The model calculates the environmental costs for every possible lifespan of a building and plots these values along the corresponding lifespans (see Figure 6.2a). Both main parts of the framework are now discussed separately.

7.2 THE PARAMETRIC FRAMEWORK

The framework developed in this research is based on the two main parts stated in section 7.1. The framework is based on a parametric model constructed in Grasshopper, a parametric plugin of the Rhino software package. Within this model, multiple component groups can be found with each their own goal.

In general, the framework consists of some input parameters (which can be changed easily), these parameters can be divided into geometric parameters (floor height, grid size etcetera) and material parameters (reuse and recycle percentages, technical service life of the material) or a combination of both (Building Circularity Index). The geometric parameters can be easily changed on the fly by the help of a slider, after which the design is reassessed.

In this model, it has been decided to not separate the reference designs from the environmental impact calculation by means of linked files, in order to increase the readability and understandability of the model. Nonetheless, if this model is continued and to be used for multiple designs, it is better to disconnect both parts because it increases flexibility in use. This way, the model can be further developed separately, by several parties, while the environmental impact calculation method is not affected. A desirable requirement in the early design phase.

Lastly, user-friendliness of the model is an aspect to further develop. The parametric model as set up now has no user interface, so only people familiar with the model set–up can use it. The user-friendliness therefore leaves something to be desired. In addition, the model has become so elaborate that it can no longer be run in real time in order to compare designs, since each calculation takes around 20 seconds. As a solution for this, the model will have to be converted into a cloud-based solution, as offered by White Lioness in their packhunt.io platform.

7.3 REFERENCE DESIGNS

A parametric approach has been chosen such that an environmental impact calculation can be made efficiently based on whatever desired geometry. However, during this study it was decided to choose a "dummy design", which is used as a reference on which the results and conclusions in this study are based. The risk being that general conclusions are drawn from specific starting points. The sentence "A timber structure is more environmentally friendly than a steel structure up to a lifespan of [xx] years" therefore can only be stated for these specific designs.

The reference designs have been chosen in such a way that they provide the most comparable and standard design possible, such that the different materials can be compared to a certain extent. An important assumption is that an as equivalent as possible functional unit is pursued, which means the designs can be not as optimal or realistic as possible for every material considered. This implies that for one material an optimal and realistic structural design may have been used, while this does not produce any realistic results for another material. However, the designs do aim for an "average" design, with an average amount of m^2 GFA per kg of construction material.

Although fire resistance does not fall within the scope of this study, the current reference designs contain significant differences in functional unit with regard to their fire resistance. Where a concrete framework already is fire resistant, it is not present with the steel and wooden skeleton, so that fire-resistant measures still have to be added here (such as Promatect coating). This results in a non-uniform functional unit.

Furthermore, all structural calculations were made by means of rules of thumb. This can cause the dimensions of the designs to be too coarse, hence a higher environmental burden is calculated. However, an optimized design of the steel design was also developed using the FEM plugin Karamba, which resulted in a design that does not deviate significantly (10%) from the design based on rules of thumb.

The calculations based on rules of thumb have only been validated for the beams. These structural elements loaded on bending are most sensitive to a load alteration. Therefore, only these elements have been validated. However, there is a risk that the rules of thumb for the columns or sleepers will not suffice, since they are not validated.

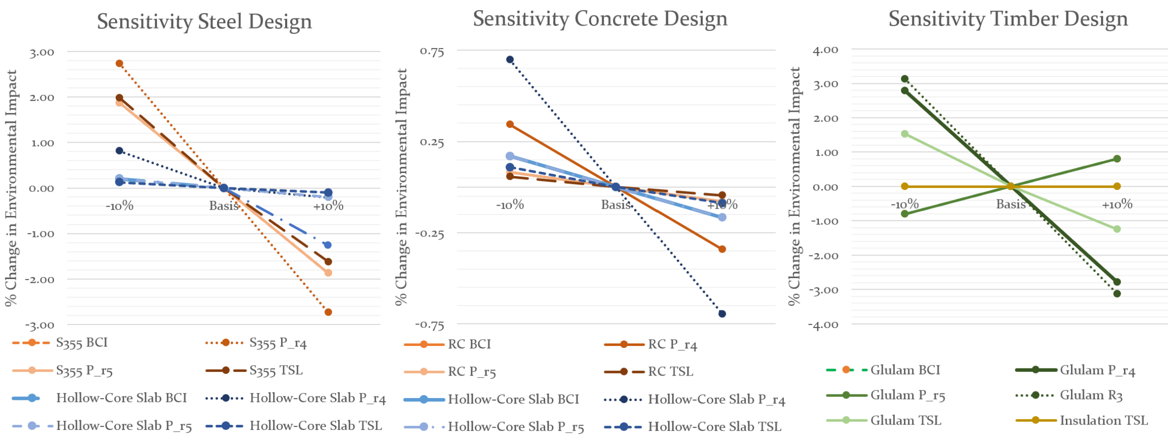
Upon validation of the timber beam, it has been found that the rules of thumb as stated in Jellema 3 [Hofkes et al., 2004] do not satisfy for beams with an center distance of l, due to the fact that they are intended for a center distance of $\frac{l}{2} - \frac{l}{3}$. Consequently, the rule of thumb has been adjusted from $h = \frac{l}{20}$ to $h = \frac{l}{10}$. This new "rule of thumb" still holds after validation. However, this is not a generally validated and thus unofficial rule of thumb, so much that there is a risk that it will either result in too low or too high outcome. It is therefore desirable, if this is possible in the future, to base all designs on an optimization process which, until now, has only been possible for a steel design in a straightforward manner.

7.4 ENVIRONMENTAL IMPACT CALCULATION

7.4.1 Sensitivity analysis

A sensitivity analysis is performed in order to reduce the uncertainty and increase the robustness of the results. This analysis gives insight in which input parameter should be further researched in order to solidify the model. All parameters are assumed independent, and correlation between different parameters is outside of the scope of this study.

The sensitivity analysis is only performed on the end–of–life allocation equation parameters. This means, other parameters such as those for the structural calculation, or Nationale MilieuDatabase (NMD) values of the LCA are not included. It is chosen to only include the input parameters for the end–of–life equations as these equations are newly developed in this research and supposed to be used as a general methodology. The actual sensitivity analysis is performed in Appendix J. Only the result of the analysis is shown here. The sensitivity analysis is performed on the results of scenario 4, which includes both the use of a donor structural framework as the future remountability of the design, see subsection 4.4.2 and subsection E.1.4.



(a) Results steel design. **(b)** Results concrete design. **(c)** Results timber design.

Figure 7.1: Results of the sensitivity analysis for the end–of–life allocation equation parameters, using scenario 4 of subsection 4.4.2. This scenario assumes both the use of a donor structural framework as the future remountability. For numerical values see Figure J.1.

Steel

Figure 7.1a shows that for the steel reference design, the percentage of the structure which is constructed out of reused elements has the highest influence on the environmental impact when scenario 4 is used.

A general trend can be observed: The parameters used for the S355 steel elements have a higher sensitivity than those for the concrete hollow–core slab in the steel design. This is remarkable, because the environmental impact of the hollow–core slab is higher than that of the steel framework, according to the results of Figure 5.3. This is due to the high environmental impact per kg of steel, in relation to the impact per kg concrete. Even though the amount of kg steel is 8 times lower than the amount of kg concrete, the environmental impact is only 1.2 times lower. Therefore, a relatively small deviation in reuse rate, circularity score, or even lifespan has a big influence on the steel part of the structure.

Lastly, the input parameters of the steel structure are significantly higher than those of the hollow–core slab ($BCI_{steel} = 0.76$ vs. $BCI_{hollow-core} = 0.21$), such that a 10% relative change actually is a higher absolute change.

Concrete

Figure 7.1b shows that for the concrete design the percentage of the structure which is constructed out of reused elements (P_{R4}) has the highest influence on the result, which is similar to the result of the steel design. This is to be expected as this parameter has a direct impact on the virgin amount of material needed for the design, while parameters such as Building Circularity Index (BCI) or P_{R5} indirectly influence this amount.

An obvious difference between the results of the steel and concrete design is the sensitivity to the Building Circularity Index. This is about two percent for steel, whereas it is 0.08 percent for concrete. This big difference is due to the same factor as the difference in impact of the Building Circularity Index in the steel design for the S355 steel and the concrete hollow–core slab. This conclusion can also be drawn generally for the concrete design in relation to the steel design. Where a 10% change in input for the steel design has an average effect of 0.72%, this change only has an effect of 0.15% in the concrete design. Moreover, the timber design has an average sensitivity of 1.8%, even higher than the steel design. Conclusions can be drawn that the concrete design is less sensitive to changes in parameters than both the steel and timber design.

In general it can be concluded that a material which has a higher environmental impact per kg has a relatively high sensitivity to the various parameters. On the contrary, this means that concrete has a lower sensitivity due to the low impact per kg of the material.

Timber

The average sensitivity of the timber design to changes in input parameters is the highest of all materials. Since the incineration of timber has a major (positive) impact on the environmental costs of the building, the highest sensitivity lies with the incineration percentage at end–of–life (R_3). When the incineration has a large impact, the percentage of wood used for incineration has a large impact as well. In addition, a higher initial percentage to start with means that a 10% relative difference is greater in absolute values.

In fact, this analysis shows that burning wood at the End–of–Life (EoL) is better for the environment than reusing that same wood in a new building. This can be deduced from the negative sensitivity of the reuse percentage at EoL (P_{R5}). Of course, this is not true in reality, but rather a flaw in the model. When timber from the current building is burned, it disappears from the cycle and as a result, no negative impact is counted for, while when the material is reused, part of the impact from the next life cycle is included in the impact of the current life cycle. As a result, a part of the virgin impact of a new building should be included in the current buildings environmental impact. However, this has not yet been implemented in the current method, which entails a risk.

The result of this flaw is that for the current method, all lifespans shorter than the Technical Service Life of timber, $TSL_{timber} = 75$ years, the environmental impact is calculated too favorably for the timber design, due to an excessive amount of bonus is taken into account from the incineration of wood. If the technical lifespan of timber is not utilized, the environmental impact therefore is lower, which is a contradicting statement. The closer the building lifespan RSL is to $TSL = 75$, the more realistic the environmental impact of timber becomes.

7.4.2 Analysis of the results

7.4.2.1 *The standard scenario*

The upward trend of steel in Figure 6.2b indicates the small reuse percentage a steel structure has. 4% of the structural steel elements is reused at its end–of–life, which profits a short lifetime of a steel structure due to its reuse potential. When the material end of lifetime is reached, no reuse is possible and the benefit disappears.

Looking at the timber line in Figure 6.2b, the step in impact at 75 years is due to the service life of glued laminated timber of 75 years. The model calculates a rebuilt of the structure after 75 years. The timber structure discretely increases at 30 year intervals due to the service life of the insulation and gypsum plates of 30 years. These sound–proofing measures increase the impact of the timber structure in a significant way. The low impact of the timber design is mostly due to the difference in approach between the different materials. The developed model includes the incineration of timber at the end–of–life, which averagely decreases the environmental impact by 40% (see Figure 7.2. This is shown in the sensitivity analysis of subsection 7.4.1, where parameter R_3 is varied.

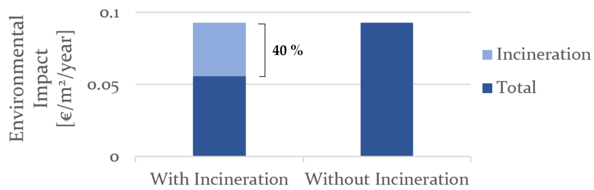


Figure 7.2: Environmental impact of the case–study for RSL = 50 years, with and without incineration.

The concrete impact stays the same throughout the 150 years considered because there are no benefits of reuse. No steps in impact show due to the fact that the assumption is made a concrete structure has Technical Service Life of 150 years.

7.4.2.2 *The impact of the donor structural framework*

The even decrease of impact across all lifespans in Figure 6.3 is due to the fact that only the reuse percentage is adjusted (P_{R4}); a factor that is not time-dependent. A constant reduction is the result. For steel, this results in a big decrease due to a high percentage of the structure that can be constructed from donor elements (75%). In contrast to concrete, which only uses 20% donor elements thus results in a smaller reduction.

7.4.2.3 *The impact when the probability of reuse is considered*

When the remountability of a steel structure is included in the Environmental Impact Calculation (EIC), this reduces the environmental impact for short lifespans (< 72 years), but increases the environmental impact for buildings with a lifespan longer than 72 years. The cause of this is the reuse part of Equation 4.11, which is shown in Equation 7.1.

$$\begin{aligned} &P_{R5} \cdot BCI(n \cdot E_{reusing,EoL} - (1-n)E_v^* \cdot K_{reu}) \\ &\text{With:} \\ &n = \frac{\text{Service Life of the building}}{\text{Technical Service Life of the material}} \end{aligned} \tag{7.1}$$

The factor n is responsible for this shift. The amplitude of this difference in impact between a short and long lifespan is caused by the factor $P_{R5} \cdot BCI$; the percentage of reused elements times the probability that elements are reused at all. For steel this combined value is high, that is, a standard steel structure can be described as "circular" due to its connections being relatively easy to disconnect. The difference between the average recycling percentage ($R_5 = 0.08$) and the calculated percentage based on circularity ($P_{R5} \cdot BCI = 0.57$) therefore is large.

When looking at the concrete design, it is striking that this shift is considerably less than that of its steel counterpart. The "Scenario 1: Average" line is barely rising, and the line of "Scenario 3: remountability" rises only slightly. This is not only due to the low average recycling rate of concrete ($R_5 = 0$), but even when circularity is taken into account, this percentage only increases slightly ($P_{R5} \cdot BCI = 0.04$).

The increase in impact over the lifespan of a timber building which includes remountability is somewhere in between the values of concrete and steel. The cause of this once again can be found in the percentage of reuse when circularity is or is not included, equal to the steel and concrete results.

Despite the fact that the origin of the relative differences in environmental impact is in the reuse percentage, the turning point of whether taking remountability into account is advantageous or disadvantageous is different for every design considered. For a steel structural design, this point occurs at 72 years, while the concrete design gets to this point only after 120 years and timber already after 36 years. These differences can all be attributed to the combination of an overall reduction in environmental impact through reuse in general and a shift in slope of the graph from the factor n. This trend can be compared with the general adjustment of the original PEF equation into an equation which takes both reuse and the remaining service life factor (n) into account, which can be found in Figure 4.8b.

7.4.2.4 *Comparing a standard design with a remountable design (DfD applied)*

When the standard and highly remountable designs are compared in Figure 6.8, a few thing stand out. When looking at every design separately, the graphs shows that at relative short lifespans, a highly remountable design is more environmentally friendly than a standard design out of the same materials, while longe lifespans favor standard designs. However, the turnover point where this switch happens differs for every material thus design.

Due to the long Technical Service Life of steel and concrete, their corresponding turnover points happen at 137 and 120 years respectively. The fact that the steel design is longer suitable for DfD is due to the fact that a higher percentage of steel elements can be reused compared to concrete elements. In this model, only the probability that a structure is reused (BCI) is changed if DfD is applied, but the amount of materials being reused (P_{R4}) remains identical. It can be argued that this should change as well, if a building is constructed such that it can be deconstructed efficiently. Lastly, timber only has a Technical Service Life (TSL) of 75 years, which results in a turnover point at 30 years.

7.4.2.5 *Comparing the impact of a highly remountable design with a design which uses a donor framework.*

When analyzing Figure 6.9, a general observation can be made; A timber design is the most sustainable solution for short to average building lifespans, while for longer lifespans, steel and concrete designs are more sustainable. In a steel design, using a donor framework significantly reduces its environmental impact in comparison with applying Design for Deconstruction, while this latter concept has very little impact to a concrete design. This results in steel and concrete being the most sustainable solutions at longer lifespans, only if a donor framework is used in the steel design.

7.4.3 Possible flaws of the created impact calculation method

The developed environmental impact calculation method brings does not only bring benefits, but creates some possible problems as well. The flaws of the model created are stated as follows:

- The developed allocation equation allocates future reuse partly negatively (from the next life cycle) while incineration/disposal ends the life cycle, therefore no extra impact is included from the next life cycle. This issue is already stated at the timber sensitivity analysis of subsection 7.4.1. This flaw should be adressed before the model is being used.
- The assumptions regarding the Technical Service Life of the materials are not always well founded. It has proved difficult to find out what the technical lifespan of a certain material or element is. Often, a minimum lifespan is specified by the manufacturer or is designed according to the Eurocodes for a certain Functional Service Life. However, this is not the timespan that the

material is technically "exhausted". Further research must show what these lifetimes are for the different materials, since they can have a major impact on the results. (see the discrete step in impact of the timber design at 75 years in Figure 6.2b).

- The number of times of dismantling and rebuilding cannot be adjusted quickly to compare certain solutions (75 years in 1 location or 25 years in 3 different locations). This is due to the different constructive principles which are used for the buildings which are 75 years in 1 place or 25 years in 1 place, which makes a comparison more difficult. This is not included in the model, but can be added relatively easy later on.

- Modifying an existing allocation method into something for which it was not originally designed for is dangerous. It is probably better to develop an entirely new method specifically designed for the use in a circular economy. The method which is created here is a method meant for the transitional phase when linear and circular still intertwine.

- Sometimes, if this could be substantiated, the NIBE EPD app values (such as for the virgin production of steel) were deviated from because they would not be realistic according to new research [Maastrigt, 2019]. In other places, NIBE values have been used while these may not be the most realistic values. For example, the environmental impact of burning wood is in fact under great pressure [Woutersen et al., 2017; Duurzaamnieuws.nl, 2019]. To a large extent, this impact ensures that the timber design has the lowest impact in comparison with the steel and concrete design. If the NIBE values are further investigated and it appears that the combustion credits are incorrect, this can negate a part of the outcome of the research. Although the results then have to be revised, the established methodology still stands. In a general sense, it may be risky to sometimes follow NIBE and sometimes not, but on the other hand, this does lead to the most realistic results for now.

7.5 STRENGTHS OF THE DEVELOPED MODEL

The strengths of the developed model have been elaborated per item, where Table 7.1 shows the differences and similarities of the developed model in comparison with the existing NIBE EPD app.

- Until now, the default lifespan has been determined by the function of the building (Functional Service Life). By using the model developed here, this lifespan can be determined on the basis of sustainability requirements instead of functional requirements. The differences in environmental impact for different lifespans can easily be compared. Therefore, it is made possible to steer towards a certain lifespan, in order to determine the most sustainable construction based on the clients requirements. This is currently not possible in the Dutch construction industry.

- The entire model is parametric and therefore can be adjusted on–the–fly. Different designs can be compared easily in order to make the most sustainable design possible.

- Input parameters which are currently unclear/unfounded can be adjusted in a swift. This changes the results, but the underlying methodology is retained.

- The NMD has been developed for the linear economy, whereas the developed model can be used in a circular economy. The NIBE EPD app has a process database which only includes the current life cycle of a building (Production

— Construction — Use — Demolition). No allocation model is required for this. An update of this database has already expanded this through a Waste Scenario tab, in which the various EoL options are combined for a specific material or product. For example; recycling percentage, reuse percentage, landfill percentage, associated transport distances, database processes to be used and loss-of-quality factors. However, this has only just started and therefore the database is far from completed. This study involves the above percentages for all materials to be compared taken from literature research.

- Moreover, the model goes further than supplementing missing data from NIBE. For example, the possible reuse of structural elements for both the construction phase and the EoL phase is included. This means that both the previous, current and next life cycle of an element are included in the calculation, where the current LCA methodology only takes the current life cycle into account. This has been achieved by applying a newly developed EoL allocation equation and retrieving environmental impact data regarding processes such as the deconstruction of a building or downcycling of a material.
- A critical review regarding the current NIBE EPD data has been carried out, and where it could be scientifically refuted that this data was incorrect, adjusted data has been used, such as for the impact of virgin steel.
- The circularity of a design is included in the sustainability calculation. Something that is not possible in the current LCA methodology. Therefore, changing a construction type has a direct result on the environmental impact.

	NIBE EPD app	Update NIBE EPD app	Developed Model
Production Phase	•	•	•
Construction Phase	•	•	•
Use Phase	•	•	
End–of–Life Phase	○	•	•
Demolition	•	•	•
Disposal	•	•	•
Waste Scenarios		○	•
Transport Distances		•	•
Deconstruction			•
Recycling		○	•
Reuse		○	•
EoL Allocation			•
Donor Framework			•
Remaining Service Life			•
Design for Deconstruction (Circularity Score)			•

Table 7.1: Differences and similarities between the NMD and the developed model in terms of included LCA phases, concepts and processes.
• = fully included and ○ = partly included.

7.6 REFLECTION

Looking back on the original goal of this study, "Creating a tool which can be used in the early design phase to compare different construction variants on their environmental impact, including the DfD concept", this has been achieved and even surpassed on most points.

The above objective is defined by the three problems stated in section 1.3:

1. No assessment of sustainability in the early design phase.
2. Insufficient knowledge regarding the environmental impact of Design for Deconstruction.
3. Current LCA methodology does not consider the beyond end–of–life phase.

The first problem has been solved by making a completely parametric model, which includes the geometry, structural solutions and the environmental cost calculation of a design. However, within the available timeframe, it was not deemed possible to create a matching User Interface, as a result of which the user-friendliness of the tool still leaves something to be desired. In addition, the model cannot be run in real–time, which also does not benefit user-friendliness. However, this can be solved by adapting the model and running it in a cloud–based solution such as Packhunt.io.

The second and third problem, with regard to the Design for Deconstuction concept and therefore the beyond–end–of–life phase of an LCA have been tackled, as can be seen in Table 7.1. A more comprehensive answer to the main objectives is given in the next chapter, chapter 8.

The tool developed in this study is not intended to stand on its own in a way that anyone is able to use it. The end product of this research provides a newly developed method and a framework that acts as a kind of proof of concept on which proper tools can be built.

8 CONCLUSION

The objective of this research as stated in section 2.1:

"The goal is to develop a model which can aid the user in choosing the most sustainable construction material in the early design phase over the total service life of the building. The Donor Structural Framework and Design for Deconstruction concepts are evaluated in this process."

It can be concluded that the parametric model developed in this research fulfills this goal. Before answering the main research question in section 8.2, an answer is given to the sub–research questions in section 8.1.

8.1 SUB–RESEARCH QUESTIONS

"How to implement the Donor Structural Framework and the Design for Deconstruction concept into the existing Life Cycle Assessment (LCA) methodology?"

The conclusions of section 4.2 and 4.3 provide answers to this sub–question.

It has been proven possible to implement the Donor Framework and Design for Deconstruction concept in existing methodologies, which are based on the current Life Cycle Assessment methodology. The literature study on sustainability (Appendix A) and subsection 4.2.1 showed that the present methodology only considers the current life cycle of a building, something that is not possible when the Donor Structural Framework and the Design for Deconstruction concepts are used. In addition, the so–called End–of–Life allocation equations are not captured in this methodology, which determine the weighing factors of the environmental impact of different processes. For this reason, the reuse of materials has not yet been included in the current NMD 2.3. However, halfway through the research an update of the NIBE EPD app was released which does include some reuse processes, but does not cover nearly all materials.

In order to include the reuse of materials and structural elements, an allocation method has been chosen which is based on the current LCA methodology, the so–called Product Environmental Footprint (PEF) method. First, a part regarding reuse in general is added to this equation in subsection 4.3.2. However, this method does not consider the future of a building and its materials as well (what is the probability that the building will be reused in the future?). That is why the Building Circularity Index has been implemented in the modified PEF equation. The Building Circularity Index calculates the "Circularity Score" of a building, element or material. This score is used in the method developed here as a "probability of future reuse" factor. These modifications can be found in section 4.3.

"How to calculate the environmental impact of a steel, concrete and timber load–bearing structure and their corresponding service lives using a parametric model?"

Section 3.1, 3.2 and 4.4 provide answers to this sub–question.

A parametric model is built with two main parts:

1. The construction of the reference designs and their structural calculations.
2. The calculation of the Environmental Impact of those reference designs.

For the first part, a geometry is assumed of which the structural calculations are made. This geometry is assumed equal across all designs in order to compare all results. Due to the fact that the tool is to be used in the early design phase, no specific structural calculations are required. Together with the fact that Grasshopper in its current form is not able to optimize concrete and timber structures in a user–friendly way, it is chosen to base the structural calculation of the three designs on rules of thumb.

The Environmental Impact Calculation (EIC) is split into two main parts as well:

1. The LCA which calculates the impact of all processes involved per life cycle per kg material.
2. The 6 scenarios calculate how every process of every life cycle of the LCA is weighted in the total Environmental Impact Calculation. This is the so–called end–of–life allocation. Every End–of–Life (EoL) scenario calculates a different combination of the use of a donor framework, no use of a donor framework, Design for Deconstruction or no Design for Deconstruction taken into account.

Different input parameters for both the LCA part and scenarios were assumed due to a lack of existing knowledge and/or Nationale MilieuDatabase (NMD) data. Mostly the environmental impact of deconstructing an existing building is lacking, for which only steel data was found. Deconstruction impact for other materials therefore is assumed in subsection 4.4.1. Moreover, the Technical Service Life of each material is assumed in this research, of which little research has been done. However, the Technical Service Life can have major influences on the design choices based on environmental impact.

8.2 MAIN RESEARCH QUESTION

"How can the most sustainable construction material be found in the early design phase, taking the design for deconstruction principle into account?"

By using the developed parametric model, the environmental impact of various construction variants can be determined in the early design phase. The dimensions of a design can be adjusted by means of sliders, after which the new environmental burden of the project is calculated in real time. After calculation the model exports the results to Excel, for the purpose of different materializations or geometric variants to be compared quickly by means of graphs.

The model not only includes the Design for Deconstruction concept in the Environmental Impact Calculation, but the use of a Donor Structural Framework as well. These options have been added to the existing Product Environmental Footprint allocation method by, among other things, using the Building Circularity Index. With this addition, the probability that a structural design will be reused in the future can be calculated and thus have an effect in the environmental impact of the design.

The developed model makes it possible to calculate whether a design is best built in a certain material in the early design phase, with or without the use of a donor structural framework and including the probability of reusing a remountable structure for future purposes.

Applying the aforementioned model onto the case–study reference designs, conclusions can be drawn from these results. However, the conclusions drawn below are not general conclusions, but only true within the scope of this study and taking into account the following points of attention:

- A case–study design was used to different materials. Results with regard to sustainability scores can only be applied to this case study and are not to be considered general conclusions. By applying the same design for each material, it does not mean that the optimum design parameters were applied for every material.
- The developed model is not hypersensitive to changes in parameters, but such changes can still have a significant impact on the result. In addition, a number of important parameters have been assumed due to insufficient existing research (P_{R4}, P_{R5}, TSL).
- The developed End–of–Life allocation equation includes the incineration of timber too favorably in terms of environmental impact. This flaw in the model has major consequences for the wooden design when a lifetime is assumed much shorter than 75 years.

The results from the case–study while considering the aforementioned are as follows: The use of a donor framework always is a more sustainable solution than designing a building with deconstruction in mind, since when a donor framework is used the materials are already reused, while this is yet to be seen in the case of designing a remountable building.

In addition, a timber design with a donor framework is the most sustainable solution up to a lifespan of 75 years, although all timber design solutions within this lifespan are more sustainable than their steel or concrete counterparts. From a lifespan of 75 to 100 years, a steel load–bearing structure with the use of a donor framework is the most sustainable solution and with a lifespan of more than 100 years, concrete is the most sustainable design.

Of all the designs in which a donor framework is not used, it is striking that a steel highly remountable design is only more sustainable than a standard concrete design when extremely short lifetimes are considered ($<$ 7 years). Additionally, a timber design is the most sustainable solution until a lifespan of 75 years, while designing it highly remountable is only effective when a lifespan shorter than 30 years is expected. For designs which are expected to maintained for over 75 years, a concrete design is the most sustainable solution. Designing for Deconstruction is effective here for lifespans shorter than 120 years.

In general it can be concluded that when the burning of timber is included at the end of its lifespan, a timber design is the most sustainable solution for conventional building lifespans ($<$ 75 years). If the building has to remain standing for an exceptionally long time, it pays to use a donor framework for both the steel and concrete design, such that they have the same environmental impact. When a donor framework is not used, a concrete design is the most sustainable solution when a long service life is required.

9 RECOMMENDATIONS

- The Technical Service Life of every material (how long does a material last before it cannot be used anymore) has a big impact on the total environmental impact. However, this data is not available and many assumptions regarding this material lifespan have been made in this research. It is highly recommended to further research this field of study.

- The dimensioning of the construction is now done on the basis of rules of thumb because with the current software (Karamba), only a steel construction can easily be optimized. When structural optimization is possible for all materials, further research can be conducted to less standard geometrical shapes and designs.

- The use of the Estimated Service Life from [Landman, 2016] instead of the Reference Service Life can ensure that a realistic value for the lifespan of the building, and therefore a more realistic environmental impact, can be found. However, further research to this concept needs to be conducted before it can be applied.

- The Building Circularity Index in this study has been retained as ”probability of future reuse”. In reality, this is not a direct relation. Possibilities for a probabilistic model to determine the probability of future reuse therefore need to be further investigated.

- Not all environmental data of various materials required for this model is present in the current Nationale MilieuDatabase (NMD). That is why half of the environmental impact data comes from the NMD and the other half from literature. If the NMD is reliable and complete enough, a link can be created between the model and the NMD, such that the model database is always up–to–date, and new materials can be added quickly. In addition, an NIBE EPD app update was released halfway through the research. Therefore, this research is based on both the old and new version of that specific app. It is recommended to update the model such that all available tools of the NIBE app are integrated.

- The foundation of a building is not included in this model due to the great uncertainty in its size. However, the foundation can have a major contribution to the environmental impact due to the large amount of concrete involved. The significant difference in the total weight of each design cause the foundation to differ considerably as well. This needs to be studied in further research.

- As mentioned in the discussion, there is a flaw in the allocation method which ensures that it can be more cost–effective to either dispose or incinerate a material instead of reusing it. This flaw needs to be addressed in future use of the model.

- It is recommended to add a User Interface to the parametric model, which shows the environmental impact of different lifespans in real time. This way, everyone can work with the model without knowing the background of the model. Furthermore, it is recommended to convert the model into a cloud–based solution, such as the Packhunt.io platform. This can enhance the user–

friendliness to a great extend, by making complex real–time computations possible.

- It is recommended to separate the geometry and structural calculation from the environmental impact calculation, that is, two separate grasshopper files which are linked. In this way, the model is easier to adjust and modify for other designs.
- The model calculates the environmental impact for each lifespan, taking into account the probability of a building being reused. However, this says nothing about the difference in impact between constructing a building for 60 years and leave it in the same place versus building for 60 years and moving it every 20 years. This question has not yet been answered in this model, but can be added through further research.
- Fire resistance requirements are only included in the floor designs. These requirements are not included in the structural framework. This means that for the steel and timber design, a fire resistance covering needs to be added to the framework in order to compare the same functional unit as the concrete framework. This measure increases the environmental impact.

Lastly, user–friendliness of the model is an aspect to further develop. The parametric model as set up now has no user interface, so only people familiar with the model set–up can use it. The user-friendliness therefore leaves something to be desired. In addition, the model has become so elaborate that it can no longer be run in real time in order to compare designs, since each calculation takes around 20 seconds. As a solution for this, the model will have to be converted into a cloud-based solution, as offered by White Lioness in their packhunt.io platform.

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Part IV

Appendices

A LITERATURE STUDY SUSTAINABILITY

A.1 POLICY AND LEGISLATION

A.1.1 The circular economy principle

Climate change is a problem which occupies humanity to a large extend. In the last century, humanity has intensified the greenhouse effect immensely, due to the emission of greenhouse gasses. A main cause for this increasing rate of emission is due to the consumer focused economy we are living in, a so called linear economy. Products are produced, then used and finally processed as waste. To tackle the problem of global warming, it is essential that we make a transition from a linear to a circular economy. The ultimate goal of the circular economy principle is to decouple global economic growth from the extraction and consumption of finite resources. Instead of the use of finite resources, the foundation of economic growth should be the reuse of materials reclaimed from end–of–life products, made possible by designing products for reuse, disassembly and refurbishment [Braendstrup, 2017, p. 7]. The idea of a circular economy is based on three principles [Ellen MacArthur Foundation, 2017].

- Design out waste and pollution
- Keep products and materials in use
- Regenerate natural systems

A.1.2 European policy

As part of the goal to make a shift towards a circular economy, in 2010, the European Commission proposed the *Europe 2020* strategy. This strategy aims for the sustainable development goals set by the Ellen MacArthur Foundation from [Ellen MacArthur Foundation, 2013], which should result in a sustainable and inclusive growth within the European Union [European Commission, 2010]. As part of this strategy, the *Roadmap to a Resource Efficient Europe* [European Commission, 2011] was published in 2011. This roadmap sets out a framework for the design and implementation of future actions. It also outlines the structural and technological changes needed by 2050, including milestones to be reached by 2020.

In 2014 the European Commission proposed *Towards a Circular Economy* [European Commission, 2014] in which the building sector in specific was targeted. Then, in 2015, the European Commission adopted an ambitious *Circular Economy Action Plan*, which includes measures that will help stimulate Europe's transition towards a circular economy, boost global competitiveness, foster sustainable economic growth and generate new jobs. The EU Action Plan for the Circular Economy establishes a concrete and ambitious program of action, with measures covering the whole cycle: from production and consumption to waste management and the market for secondary raw materials and a revised legislative proposal on waste. The annex to the action plan sets out the timeline when the actions will be completed. The proposed actions will contribute to "closing the loop" of product lifecycles through greater recycling and reuse, and bring benefits for both the environment and the economy [European Commission, 2019]. The Waste Framework Directive sets a target of 70%

by weight for recycling, recovery and reuse of (non–hazardous) construction and demolition waste to be reached in 2020 [Braendstrup, 2017].

A.1.3 Dutch policy

Based on the European *Towards a Circular Economy*, the Dutch government proposed *Nederland Circulair in 2050* [Ministerie van Infrastructuur en Milieu and Ministerie van Economische Zaken, 2016]. The goal of the Dutch government is contribute to the global and European Sustainable Development goals and a energy neutral built environment in 2050. This is envisioned as follows;

By 2050, construction industry will include design, development, use, management and disassembly of structures in such a way that these objects are sustainably built, (re) used, maintained and dismantled. Sustainable construction materials are used which are in line with the dynamic wishes of the users. The aim is to build an energy neutral built environment in 2050 in accordance with European agreements and construction works make maximum use of ecosystem services [Ministerie van Infrastructuur en Milieu and Ministerie van Economische Zaken, 2016, p. 61].

With the sustainability goals in place in the building industry, the maximum allowed environmental impact of a building needed to be set in order to realize those goals. Since 2012, this performance in the Netherlands is quantified according to the Determination Method of Environmental Impact of Buildings and Civil Works (DM). In accordance with Bouwbesluit 2012, a Environmental Performance Coefficient (MPG) calculation is compulsory for all newly–built buildings in The Netherlands. This coefficient describes the energetic efficiency of a building. The arrival of the Energy Performance Coefficient (EPC) standard resulted in an incentive for the use of solar panels etc. What the EPC does not take into account is the environmental impact of the materials. Where, for example, adding a large amount of solar panels to a building counts as a positive addition in terms of sustainable energy production, on the contrary this measure adds many non–reusable materials to the bill of materials. In the Netherlands, the impact of material use on the environment is quantified by the MPG. In order to construct a building without an environmental impact, a balance has to be found between (sustainable) energy use on the one hand and material–related environmental impact on the other. Where the EPC has had a hard (increasingly stricter) threshold value for years, a threshold value for the MPG coefficient only exists from 2018. This MPG threshold value is $1\ €/m^2/year$. This value will become stricter in the future, and therefore more decisive.

A.1.4 Relevance

Due to the European and Dutch legislation emphasize the material–related environmental impact increasingly, lowering this impact of future buildings is of great importance. Therefore, a user–friendly tool which can make a quick assessment of the construction material with the lowest environmental impact for a specific project can focus on reducing this environmental impact in the design phase.

A.2 MATERIAL–RELATED ENVIRONMENTAL IMPACT

In subsection 1.2.1 the current state of the Dutch building sector is mentioned, along with the future need for a decrease in the material–related environmental impact. The calculation of this specific environmental impact is elaborated in this section. There are several terms involved in getting an approved environmental impact calculation in the Dutch building sector. In order to give a general view on the different documentations used in the Netherlands, Figure A.1 is used as a guideline for the terms elaborated in this section.

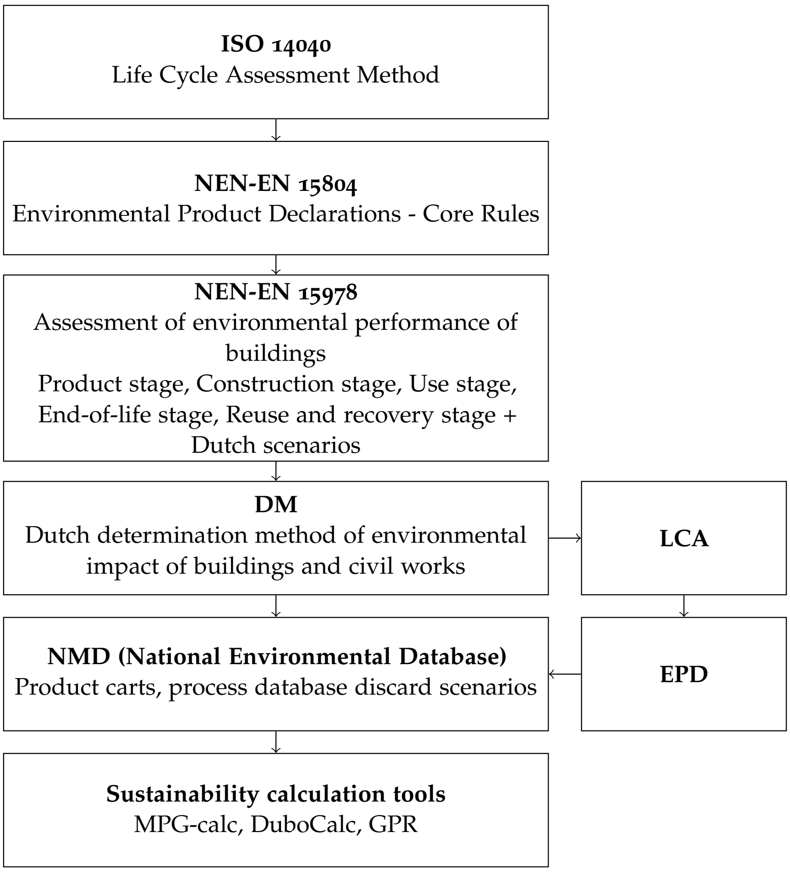


Figure A.1: Environmental impact calculation system

In section 1.2 the Dutch system of sustainability assessment and its terms are shortly elaborated. In this subsection and the next these are elaborated further.
In the Netherlands, testing a sustainable building is made up of various steps. Ever since the "Bouwbesluit" was implemented in 2012, it is mandatory to include a calculation for the material–related environmental impact when submitting a building larger than 100 m^2. This calculation is made following the The Dutch Method of determining the environmental impact of buildings and civil works (DM), which was developed by Stichting Bouwkwaliteit (SBK) and is based on the European codes NEN-EN 15804:2012 and NEN-EN 15978. Results of this method from various construction materials and processes are assembled in one environmental database, the Nationale MilieuDatabase (NMD). The user of this database can be sure that the different materials, processes and products are assessed in the same way and therefore can be used to compare design alternatives.

The NEN-EN 15804:2012 is the European standard on how to perform a Life Cycle Assessment (Life Cycle Assessment (LCA)). in this assessment the environmental effects are determined for all life phases of a material (from raw material extraction, production, use, demolition/disassembly, recycling/reuse to final waste processing). The result of such an assessment is a product sheet of the total environmental impact of a product/material. This product sheet is called an Environmental Product Declaration (Environmental Product Declaration (EPD)). An EPD is constructed of 11 different Environmental Impact Categories. All these categories have their own weighing factor, a factor which represents the costs to eliminate one kg of its corresponding equivalent unit from the environment. The 11 impact categories including their equivalent unit and weighing factors, which are included in the

NMD, are shown in Table A.1. The environmental impact categories are measured in equivalent units. This means that for instance the Global Warming Potential (GWP) is measured in kg CO_2–equivalents. In this equivalent unit not only CO_2 is processed, but also other chemical substances which worsen the GWP, such as NO_2 or CH_4 [Silvius, 2016, p.7].

Environmental Impact Category	**Equivalent Unit**	**Weighing Factor [€ / kg equivalent]**
Abiotic Depletion (AD)	Sb	0.16
Global Warming Potential (GWP)	CO_2	0.05
Ozone Layer Depletion (ODP)	CFC−11	30.00
Photochemical Oxidation (POCP)	C_2H_4	0.06
Acidification (AP)	SO_2	4.00
Eutrophication (EP)	PO_4	9.00
Human Toxicity (HTP)	1.4−DB	0.09
Freshwater Aquatic Ecotox. (FAETP)	1.4−DB	0.03
Marine Aquatic Ecotox. (MAETP)	1.4−DB	0.0001
Terrestrial Ecotoxicity (TETP)	1.4−DB	0.06

Table A.1: Environmental Impact Categories following DM with their corresponding equivalent units and costs [SBK, 2019].

A.2.1 Environmental costs

An LCA is made of a product or raw material. From this LCA follows an EPD. It states how much impact (e.g. in kg/m^3) the product has on different **eics!** (**eics!**). In the Netherlands, a total of 11 impact categories are examined. The emission of a product is subdivided into the different scenarios of an LCA (see subsection A.2.2). For example, there is 0.012 kg of CO_2 emissions during raw material supply (A1). When products can be reused, the impact categories of phase D are calculated, which in that case are negative (Reuse of materials reduces the total impact of the product). Therefore, all 11 impact categories must be calculated for each scenario.

When the amount of impact has been determined for each Environmental Impact Calculation (EIC) (the impact per category of all LCA scenarios are added), these values are multiplied by the relevant weighting factors. These weighting factors convert the environmental impact in kg (CO_2, CFC−11 etc) into a shadow price. This shadow price represents the costs required to reverse the environmental impact [Silvius, 2016].

$$\begin{aligned} \text{shadow } €_{per\ impact\ category} &= \text{impact factor [kg eq/unit material]} \\ &\quad \cdot \text{weighing factor [€/kg eq]} \end{aligned} \tag{A.1a}$$

$$\text{total shadow } €_{per\ unit\ material} = \sum \text{shadow } €_{per\ impact\ category} \tag{A.1b}$$

$$\text{Total shadow } € = \text{mass material} \cdot \text{total shadow } €_{per\ unit\ material} \tag{A.1c}$$

Example for a fictional steel product:
(Eventually, all material costs need to be summed up)

$$\begin{aligned} € 26.10 = 1500\ kg\ steel \cdot \sum(&0.05\ €/kg\ CO_2 \cdot 0.3\ kg\ CO_2/kg\ steel\ + \\ &0.02\ €/kg\ C_2H_4 \cdot 0.12\ kg\ C_2H_4/kg\ steel\ + \\ &...) \end{aligned} \tag{A.2}$$

A.2.2 Life Cycle Assessment

As mentioned in subsection 1.2.1, the DM uses the Life Cycle Assessment methodology to calculate the environmental impact. An LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope. The relative nature of LCA is due to the functional unit feature of the methodology. This relative nature ensures that the outcome of an LCA is not meaningful on its own, but it has to be compared to other LCAs with the same functional unit. An LCA does not predict absolute or precise environmental impacts [NEN, 2006, p.9].

A.2.2.1 *LCA phases*

An LCA is standardized by the (NEN-EN-ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework) and the (NEN-EN-ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines).
There are four phases in an LCA study:

1. *The goal and scope definition phase*
   The scope, including the system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA. As this research aims to compare different structural designs of a building, the scope of the LCA is the load–bearing structure, excluding the substructure. The foundation is not taken into account because of its uncertain nature due to the uncertainty in soil properties in the early design phase. The depth of this assessment will be far more general than one performed after the design has been finalized.

2. *The Life Cycle Inventory (LCI) phase*
   An inventory of input/output data with regard to the system being studied. It involves collection of the data (quantify materials, use of energy etc.) necessary to meet the goals of the defined study. Allocation of different life cycle scenarios (Phase C and D).This results in a table with all emissions of all materials in all life cycle scenarios regarding the Product Category Rules (PCR) (see Figure A.2).

3. *The Life Cycle Impact Assessment (LCIA) phase*
   The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance. In this phase the data is entered into an Excel calculation sheet which calculates the environmental impact per category and the EPD table is made.

4. *The interpretation phase*
   Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

[NEN, 2006]

A.2.2.2 *Fast–track method*

Vogtländer divides the LCA methodology in two groups, the classical and the fast–track LCA.
In the first method, the assessment is carried out from scratch and the methodological focus is on the LCI and the LCIA. This type of LCA is mostly used as a check at

the end of the design phase.
In the fast–track method the output of several of classical LCA is used as input for the fast–track LCA. The methodological focus is not on the LCI and LCIA, but on the comparison of design alternatives [Vogtlander, 2012, p.2]. The fast–track method consists of the same four LCA phases which are stated in subsubsection A.2.2.1. Because this research aims to compare structural designs in the early design phase, a variant of the fast–track LCA is chosen in this thesis.

When performing such LCA, multiple difficult questions arise like: What are the system boundaries? How do we allocate the environmental burden to the different products which are output of the system? How do we deal with the recycling or reuse of products? To deal with these issues in a well–structured manner, Product Category Rules (PCR) for Environmental Product Declarations (EPD) are used as a guideline for the model in this research. As seen in Figure A.2, the total life cycle of a building is separated into several distinct stages. Every stage has its own scenarios and every scenario has its environmental impact for every material used.

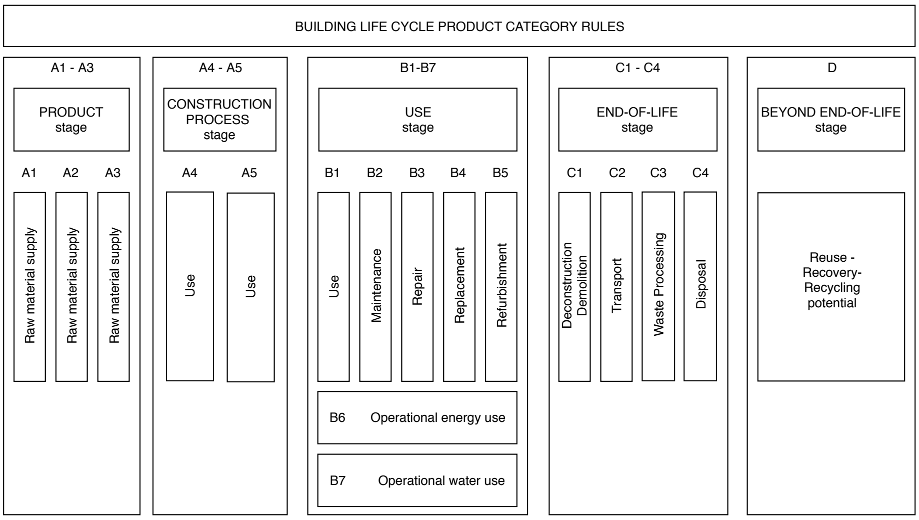


Figure A.2: Product Category Rules following [NEN, 2006]

A.2.2.3 *System boundaries*

For this research, the system boundaries can be described in the phases based on NEN-EN 15804: the production phase (A1-3), construction phase (A4, A5), end-of-life phase (C1-C4) and reuse/recycling phase (D), see Figure A.2. When assessing an EPD for building structures, it is mandatory to include phases A1-A3, C3 and C4 and D according to Dutch legislation, which corresponds to a cradle-to-gate plus end–of–life analysis [SBK, 2019; Lankhorst, 2018]. The use phase (phase B) is not taken into account, because it is assumed phase B has a relatively low impact on the total environmental impact of the load–bearing structure. Trabucco et al. found no significant impacts during this phase regarding e.g. impact on daily energy consumption, maintenance and suitability to changes. A building structure is often designed for its assumed life-time, so direct impact of this phase on the environmental impact is assumed to be small [Trabucco et al., 2016].

As mentioned before, as an extension from the Dutch legislation, the system boundary regarding reuse and recycling are covered in an rather extensive way. Which End–of–Life (EoL) formulas can be used is elaborated in section A.3. How these formulas are implemented regarding the EoL scenarios in the parametric model is touched on in section 4.4. In short, not the whole assessment is executed for the structural materials, but reuse and recycle percentages found in literature are used. This means, energy and environmental impact needed for Design for Deconstruction (DfD) is not taken into account in a comprehensive manner, but in a rather general way.

A.2.2.4 *Functional Unit*

The functional unit defines the way in which the identified functions or performance characteristics of the product are quantified. The primary purpose of the functional unit is to provide a reference by which material flows (input and output data) of construction product's LCA results and any other information are normalized to produce data expressed on a common basis. The functional unit is used as a denominator to provide the basis for the addition of material flows an environmental impacts for any of the life cycle stages [NEN, 2013a].
For an LCA performed in the construction sector, a functional unit of $€/m^2/year$ is used.

A.2.2.5 *End–of–Life*

The life cycle of a building has the basic system as described in Figure A.3. There are three main output flows to be concerned:

- **Reuse:** By–products which can directly be used in other product systems. This could be steel beams which can directly be used in other buildings in the future. Reuse is the preferred way of keeping materials in the life cycle, due to its low environmental impact. The Design for Deconstruction concept uses this output flow.
- **Recycle:** These are the materials which need further processing in order to be of any function in a future product system. This can also be steel, or concrete which can be recycled to aggregate. Recycling can mean upcycling as well as downcycling. Recycling can be seen as a lower level of keeping materials in the cycle.
- **Demolition:** Waste material that can not be reused or recycled and thus goes to a landfill or waste incineration. This is not preferred as the materials are not being kept in the cycle.

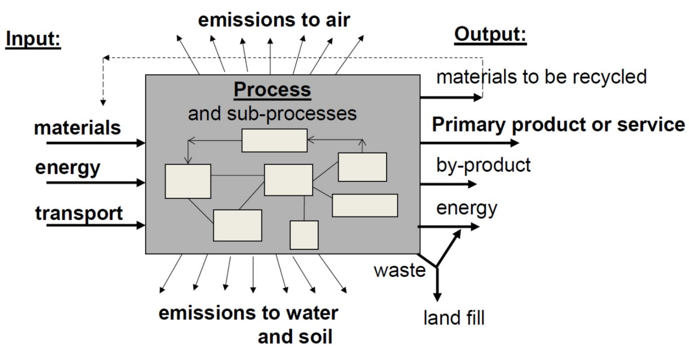


Figure A.3: Different output emissions in an LCA diagram, [Vogtlander, 2012, p.43]

The most consistent way to handle by–products in LCAs for product design is via so called 'credits'. A credit is a negative eco-burden, caused by the effect that the by-product causes the avoidance of the eco-burden of the production of that product elsewhere in the market [Vogtlander, 2012, p.44]. What the impact of this End–of–Life allocation is on the LCA is further elaborated in section A.3.

A.3 DESIGN FOR DECONSTRUCTION

This section will firstly introduce the DfD concept and its place in the circular economy, in order to find a place to implement it into the LCA methodology of section 4.3. After this place is found, different End–of–Life allocation formulas are compared in Appendix B. section 4.4 continuous on these formulas found in literature, but translates them into concepts and scenarios which can be used in a model.

DfD is a concept which goal is to increase resource and economic efficiency and reduce pollution impacts in the adaption and eventual removal of buildings, and to recover components and materials for reuse, re-manufacturing and recycling [Guy, 2006]. To this date DfD is still not used widely, mostly because of its higher initial costs of a building. Two other causes are the high labor costs of disassembly and the time this process takes. In a market such as the construction industry where time is already a big factor (costs skyrocket with time), this is not widely accepted. Last but not least, buildings in modern society are not typically designed to be deconstructed and if they are, the reuseability Bill of Materials (BoM) is not well documented. In the Netherlands however, this documentation is coming in the form of Madaster, a Material version of Kadaster. Madaster acts as a library and generator for material passports, with the aim to have insight in which materials (and structural elements) are available for reuse at what place. Future versions of Madaster will include a Building Circularity Index (BCI), which will be included in this environmental impact model as well.

A.3.1 Levels of circularity

Reusing and recycling are closely entwined terms, but they differ on some important areas. Both terms are based on the implementation of the strategy for sustainable Europe in the building sector through the reduction of construction and demolition waste. This can be achieved on three different levels, namely at building (transform, so reduce and reuse), structural element (reuse) and material level (recycle). As can be seen in Figure A.4, the preferred circularity level in this thesis is reuse, if not possible recycling and lastly landfill.

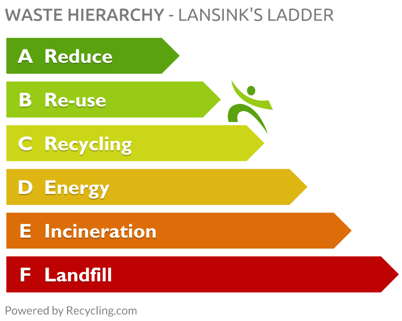


Figure A.4: Lansink's ladder on circular economy strategies [Lansink, 2015]

These levels correspond with a certain method and LCA phase where the product is reintroduced in the system and a corresponding environmental impact due to its processing. These relations are visualized in Figure A.5 and summarized in Table A.2. The flowchart shows the relation of Lansink's Ladder and the Product Category Rules of an LCA. Transforming a building has the least environmental impact because the method enters the new life cycle in the use phase. The next best method is reusing structural elements due to its introduction in the construction phase. Lastly, recycling a materials is the least environmental friendly choice due to the method re–entering the life cycle in the early material production phase. In short, the earlier a material re–enters the product life cycle, the lower the environmental benefits it creates. As transforming a building is out of this researches scope, only the concepts of reuse and recycle are discussed.

The definition of reuse in this thesis is thus defined as: *the process when structural element is used again for the same structural purpose or another purpose in the built environment* [Hradil et al., 2014].
While the definition of recycle can be defined as: *the process of collecting a waste product and reprocessing it so that it can be used once again.*

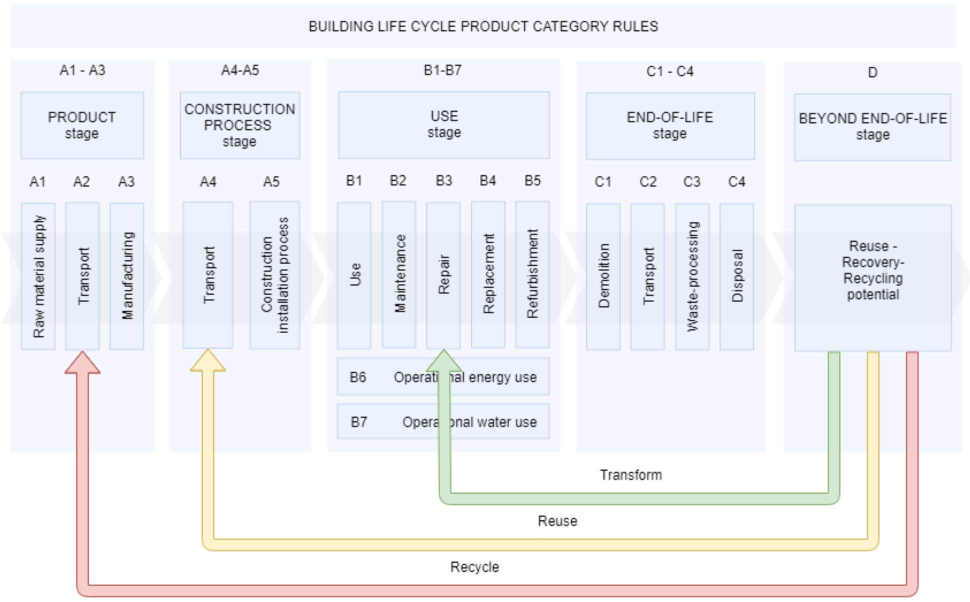


Figure A.5: Definition of transforming, reusing and recycling following the Product Category Rules of LCA methodology

#	Sustainability level	Method	LCA introduction phase	Environmental impact
1	Building	Transforming	Use	$\ll$
2	Element	Reusing	Construction	$<$
3	Material	Recycling	Production	$>$

Table A.2: Different levels of sustainable use of the load–bearing structure of a building.

When researching the rate of circularity of a building, there are multiple fields which need detailed investigation. These variables can be defined as follow:

1. The degree to which reused and recycled materials are applied in the construction phase of a building;
2. The expected lifetime of the materials in their current application; the longer a product can be used, the better;
3. Determine the degree of 'circularity' of materials in the future, that is to say, the degree to which these materials could be reused and recycled.

In the next sections, these three variables are researched with regard to the three chosen materials; steel, concrete and timber. The found rates will be applied in different EoL formulas, which are used in the LCA in the model.
The degree of to be applied reused and recycled materials (variable 1) is calculated by averaging the rates found in past literature and researches.

The degree to which materials could be reused or recycled in the future (variable 3) is somewhat harder to quantify — this pertains to future performance and is a combination of a theoretic number (degree of reusability/recyclability of the material as material) and an assessment (how are the materials combined into a product, and how is it mounted on or incorporated into a building). This concept is caught in the term Building Circularity Index (BCI).

B END–OF–LIFE ALLOCATION EQUATIONS

Due to this thesis being focused on the Design for Deconstruction (Design for Deconstruction (DfD)) principle, instead of the transformation principle, transformation and its environmental impact is not taken into account. This leaves method 2 and 3 of the previous section open for further research, where reuse on element level is the preferable method, due to its lower environmental impact compared with recycling on material level. However, not all materials are suited to be reused in element form. In order to level out every material on its ability to be either reused or recycled or its durability performance, different End–of–Life (EoL) approaches are researched in this section. How to allocate the end–of–life and beyond end–of–life phase into an Life Cycle Assessment (LCA) is one of the most controversial subjects of the LCA methodology. This section considers the allocation challenge brought by partitioning the benefits or "credits" and burdens at product EoL in the case of open loop recycling. Currently, LCA ISO 14040 standards do not explicitly address the issue of EoL accounting in open–loop recycling and a diverse set of methods exist to address this challenge. There is no clear answer on how to do this, and different parties have different opinions. This section focuses on the different allocation principles considered and shortly elaborated. Which allocation formulas are chosen and how they are implemented is discussed in Appendix B.

B.1 GENERAL ALLOCATION FORMULAS

In general, there are a few allocation concepts in use, which all have their pro's and con's. In Figure B.1 a general life cycle cascade of a building product is shown. Based on this flowchart, different allocation concepts are introduced. The scientific paper of Nicholson et al. [Nicholson et al., 2009] is used as a basis for these concepts, but every to be considered method is verified by other researches. The considered methods are summarized in Figure B.2 and evaluated below. Different methods are preferred for different construction materials, due to the fact that some methods favour certain materials.

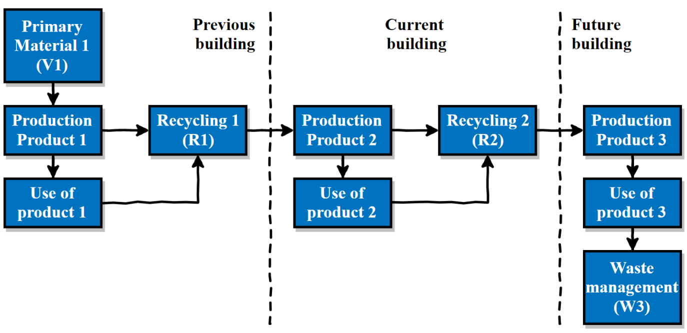


Figure B.1: Life cycle cascade of product material flows and processes involving open loop recycling for 3 life cycles [Nicholson et al., 2009, p.2]

Method	Description	Formula
Cut-off method	Loads directly caused by product are assigned to that product [13].	$L1 = V1, L2 = R1, L3 = R2 + W3$
Loss of quality method	Assigns load to products in relation to their relative loss of quality in each step [13].	$L_i = \frac{Q_i}{\sum_{i=1}^{n} Q_i} \times (V1+R1+R2+W3)$
Closed loop method	Applicable to materials that do not experience significant losses in quality when recycled [14].	$L1 = L2 = L3 = \frac{V1 + (R1+R2) + W3}{n}$
50/50 method	Virgin material production and waste treatment are allocated to the first and last products in equal proportions [13, 15].	$L1 = \frac{V1+R1+W3}{n\text{-}1}$, $L2 = \frac{R1+R2}{n-1}$ $L3 = \frac{V1+R2+W3}{n-1}$
Substitution method	Recycled material substitutes primary; accounts for lost material and recycling burdens [16].	$L1 = (100\%\text{-}r\%) \times (R1) + r\% \times (V1+W3)$
Qi is the quality of material (quality ratios can be computed using market pricing data for primary and scrap materials), n is the number of life cycles, and r is the amount of primary material needed in secondary material production to account for lost material in the recycling process.		

Figure B.2: Description and formulas for different EoL allocation methods, variables as described in Figure B.1 and defined below [Nicholson et al., 2009, p.2]

- In the **cut–off method**, a product made out of primary materials carries the environmental burdens of those primary materials and a product made out of secondary materials carries the environmental burdens of the recycling activities of those secondary materials [Vogtländer et al., 2001, p.3]. This is the most straightforward method of allocating.
- The **loss of quality method** is preferred for the calculation of concrete, due to its limited recycling ability and its loss of quality after the first cycle (from concrete to aggregate or road foundation). This method can be used for timber as well, as timber also reduces in quality after each recycling or process.
- In the **closed–loop method**, used products come back to the original manufacturer and components or materials are used again to produce new products of the same type. Hold up of materials is not taken into account. each product is equally responsible for the environmental impacts associated with virgin material production, recycling, and final waste treatment. The burden is therefore an average impact, apportioned equally among products depending on the number of times recycling occurs in the product cascade. An example for such a life cycle could be the reuse of tin Coca-Cola cans. This method can also be used for structural steel, as a simplification for the substitution method, but this is not preferable due to the method not taking the reuse and recycle rates into account.
- The **50/50 method** approximation is good when the flows of cascade material to and from the life cycle investigated are small compared to the total flow in the market, the recycling rate is decided by economic forces, and the demand and supply are equally elastic. This method is relatively easy to adept and is widely used as a method to compare different materials. However, this might not be the most realistic allocation method available, due to its strict 50/50 allocation distribution.
- The **substitution method** is preferred for the calculation of structural steel, due to the method allowing for lost material and recycling and reuse bur-

dens. This method is actually referred to as the *multi–step recycling method* of Table B.1 and this method is specified in Equation B.1.

B.2 ALLOCATION FORMULAS FOR STEEL

Birat et al. proposes different methodologies to implement reuse and recycling into an LCA in [Birat et al., 2006]. Some are more straightforward than others. The 6 models he proposed are summarized in Table B.1. The recycling and re–use of steel can be described as an open loop system. It is chosen to take the recycling of steel into account at the beginning of the life cycle instead of the end. The advantage of the new approach is:

- it fits better to the responsibility of the designer or purchaser: their choice has a direct effect, instead of shifting responsibilities to the end-users in future
- it is a better solution for systems with considerable hold-up in the use phase, or other complex situations (see the 'market mix' issue of metals below)

Model No.	Model description	Empirical formula	Comments
1	No recycling but coexistence of a virgin and recycling route	$C_{IM} \geq 2 \times EAF$	Assumes that the impact between two routes (IM and EAF) is too large. But, fails to acknowledge the fact that recycling is in its highest possible level.
2	Weighted average between virgin and recycling routes	$C_{avg} = (1-\alpha) \times C_{IM} + \alpha \times C_{EAF}$	Proposes to take into account both routes of steel production based on actual level of recycled material compared virgin material.
3	Credits for recycling	$C_{credit}^{steelengaged} = C_{IM} - (C_{IM} - C_{EAF}) \times rY$	Commonly used by LCA practitioners to account for recycling and assumes that if recycling is perfect (100%) then the IM route becomes equal to EAF.
4	One-step recycling	$C_4^1 = \dfrac{C_{IM} = C_{EAF} \times rY}{1 + rY}$	Gives due credit to recycling and recognises the fact that impact is lower when recycling is higher. It takes more pragmatic approach to mimic the real-life situation of recycling.
5	Multi-step recycling	$C_5^n = \dfrac{C_{IM}(1-rY) + C_{EAF}(rY - (rY)^{n+1})}{1 - (rY)^{n+1}}$	This model takes into account the fact that steel is recycled several times.
6	Multi-step recycling and emission credits	$C_6^n = C_{IM} - (C_{IM} - C_{EAF})(rY + (rY)^2 + L + (rY)n$	This recognises the fact that a 'credit' needs to be accorded to saving brought about by use of scrap and thus giving rise to emissions with negative value.

Table B.1: Different proposed models to integrate recycling into current LCA by [Birat et al., 2006; Yellishetty et al., 2011]

Where: IM -– integrated mill (for virgin steel making procedure); EAF — electric arc furnace mill (for scrap recycling); C_{EAF} -– specific CO_2 emission of EAF route; C_{IM} — specific CO_2 emission of IM route; α — scrap intensity ratio of steel production (ratio between virgin and recycled iron units); r -– recycling rate (amount of steel recycled compared to steel introduced in the system initially); Y — defined as the ratio of steel to scrap yield; C_{EOL} — end–of–life CO_2 emissions; $C_{credit}^{steelengaged}$ — CO_2 emissions per tonne of steel engaged (i.e. sold to downstream industry to make final product); C_4^1 — CO_2 emissions calculated by 4th model for a one-step recycling; C_5^n -– CO_2 emissions calculated by 5th model for a n–step recycling; C_5^n — CO_2 emissions calculated by 6th model for a n–step recycling; n = number of recycling cycle; L — life time of steel in products.

As found in Table B.1, Model 5 is the model generally seen as the model which is both implementable in the LCA and takes into account the fact that steel is recycled several times. However, this formula does not take the reuse of steel into account. This is added in a manual way. Lastly, the equation is normalized with the Gross Floor Area (GFA) and Reference Service Life (RSL) factor. Because the IM production route of steel is generally used for virgin and EAF route for recycled steel production, these parameters are switched for the according environmental impact factors. In case of total environmental impact this formula can be written as:

$$
\begin{aligned}
C^{n}_{5,reuse} &= m \cdot \frac{E_{vir} \cdot Virgin\%_s + E_{recycling} \cdot Recycle\%_s + E_{reusing} \cdot Reuse\%_s}{Total\%_s \cdot BVO \cdot RSL} \\
&= m \cdot \frac{E_V(1 - rY - uY) + E_{recycling}(rY - (rY)^{n+1}) + E_{reusing}(uY - (uY)^{n+1})}{(1 - (rY)^{n+1} - (uY)^{n+1}) \cdot BVO \cdot RSL}
\end{aligned}
$$

where:

$$
\begin{aligned}
C^n_5 &= \text{Environmental costs steel in its } n^{th} \text{ life cycle} \\
E_V &= \text{Environmental impact producing virgin steel} \\
E_{recycling} &= \text{Environmental impact recycling of steel} \\
m &= \text{mass of steel} \\
r &= \text{Recycling rate (amount of steel recycled /} \\
&\quad\ \text{steel introduced in system initially)} \\
u &= \text{Reuse rate (amount of steel reused /} \\
&\quad\ \text{steel introduced in system initially)} \\
Y &= \text{Ratio of steel to scrap ie. recycled content.} \\
&\quad\ \text{Amount of scrap as percentage of total amount of input material.} \\
n &= \text{number of recycling cycle} \\
BVO &= \text{Bruto Vloeroppervlak (gross floor area)} \\
RSL &= \text{Reference Service Life}
\end{aligned} \tag{B.1}
$$

$$
C_{sub} = m \cdot \frac{E_V(1 - rY - uY) + E_{recycling} rY + E_{reusing} uY}{BVO \cdot RSL} \tag{B.2}
$$

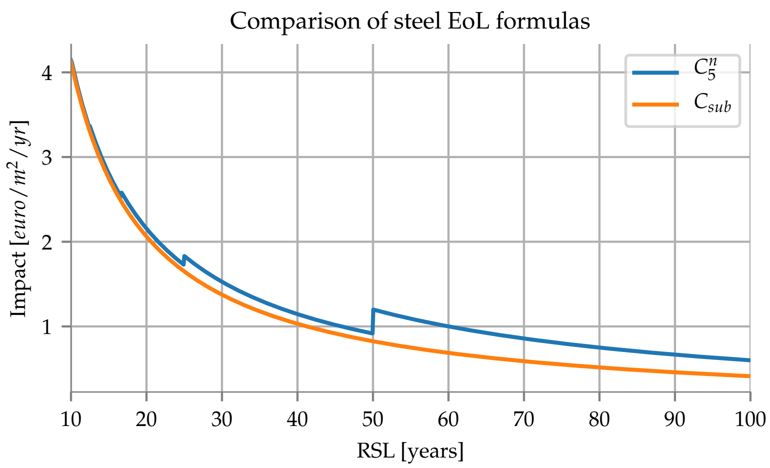


Figure B.3: Comparison between the multi–step recycling method of Birat et al. [Birat et al., 2006] and the substitution method of Vogtländer [Vogtlander, 2012]

The corresponding adjusted substitution method formula of Figure B.2 is written in Equation B.2. When comparing both formulas, a few differences can be observed. A rough conceptual graph of the comparison of both is shown in Figure B.3. Both approaches are comparable apart from the fact that the C^n_5 takes the number of recycling cycles into account, where the substitution method does not. This gives an advantages to the C_5^n, which will be used as a verification equation to compare the allocation of steel with a general allocation formula in section 4.4.

B.3 INTERNATIONAL END–OF–LIFE ALLOCATION METHODS COMPARED

Allacker et al. compared three international methods (and seven associated equations) in [Allacker et al., 2014], based on the EU policy initiatives stated in subsection A.1.2. Based on the analysis and comparison of these methods in that paper, the multi–criteria table of Table B.2 is found. The grey rows reflect the important criteria for this research, based on which a further comparison is done for the best fitting method, the Product Environmental Footprint (PEF) method.

Criteria	PAS-2050 (RC)	PAS-2050 + ISO/TS 14067 (CL)	ISO/TS 14067 (OL-LoQ)	BPX 30-323-0 (CL)	PEF	REAPro recyclability	REAPro Energy Recoverability	REAPro (CO)
1. Comprehensiveness	No	No	No	No	Yes	No	No	No
2a. Accomodates Open-loop product system	Yes	No	Yes	No	Yes	Yes	NA	NA
2b. Accomodates closed-loop product system	No	Yes	No	Yes	Yes	Yes	NA	NA
3. Distinguishes % virgin/recycled content input	Yes	No	Yes	Yes	Yes	Yes	NA	NA
4a. Considers recyclability rate	No	Yes	Yes	No	Yes	Yes	NA	NA
4b. Considers energy recovery	No	No	No	Yes	Yes	NA	Yes	NA
5a. Includes material credits	No	Yes	Yes	Yes	Yes	Yes	NA	NA
5b. Includes energy credits	No	No	Yes	Yes	Yes	NA	Yes	NA
6. Account for changes in inherent properties of materials and/or down-cycling	No	NA	Yes	NA	Yes	Yes	NA	NA
7. Avoids double counting at a system level	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8. One formula fits-all	No	No	No	No	Yes	No	No	No

Table B.2: Summary of the comparison of the production/EoL equations against the eight analysis criteria, regarding [Allacker et al., 2014].

In order to compare different materials on their sustainability level, it is preferred to have one general formula which can be used for the sustainability calculation of all materials. The PEF method is such a method with a 'one formula fits–all' approach. In the next section, the idea of PEF is explained.

B.4 PRODUCT ENVIRONMENTAL FOOTPRINT ALLOCATION METHOD

The Product Environmental Footprint PEF method is a multi–criteria measure of the environmental performance of virtually any type of product throughout its life cycle [Manfredi et al., 2012]. It has been developed by the Joint Research Centre of the European Commission and has been published in the context of the Europe 2020 Strategy — "A Resource–Efficient Europe", as stated in subsection A.1.2. This method builds on the LCA method, where the total life cycle is taken into account, from production of raw materials through end–of–life and beyond (ie. cradle–to–grave). However, where the original LCA method is able to quantify the environmental impact of certain products, it is not easy to compare different products on a sustainability level, due to its open character of inclusion of reusing and recycling. One of the objectives of the PEF is to move closer towards comparability of different products fulfilling the same function [Manfredi et al., 2012].

The PEF Category Rules may be developed in order to increase reproducibility, consistency and relevance of *PEF* studies. EoL treatment options considered include (partial) reuse, material recycling, energy recovery and disposal. As can be seen in Table B.2, the *PEF* method provides a single EoL equation which is applicable for both open–loop and closed–loop recycling. The original PEF formula is stated in [Allacker et al., 2014] as Equation B.3, where all parameters are explained in Table B.3,

$$\begin{aligned} PEF = &(1-\frac{1}{2}R_1)\cdot E_V + \frac{1}{2}R_1 \cdot E_{recycled} + \frac{1}{2}R_2 \cdot (E_{recycling,EoL} - E_V^* \cdot K) \\ &+ R_3 \cdot (E_{ER} - LHV \cdot X_{ER,heat} \cdot E_{SE,heat} - LHV \cdot X_{ER,elec} \cdot E_{SE,elec}) \\ &+ (1-\frac{1}{2}R_2)\cdot E_D - \frac{1}{2}R_1 \cdot E_D^* \end{aligned} \tag{B.3}$$

Term	Unit	Definition
E	[e.g. kg CO_2, kg SO_2 etc]	Resources consumed/emissions for the production and EoL stages of one product life cycle
E_V		Resources consumed/emissions for the acquisition and pre–processing of virgin material
$E_V^{'}$		Resources consumed/emissions for the actual virgin material substituted through open–loop recycling
E_V^{*}		Resources consumed/emissions for the acquisition and pre–processing of virgin material assumed to be substituted by recyclable materials. If only closed–loop recycling takes place: $E_V^* = E_V$; if only open–loop recycling takes place: $E_V^* = E_V^{'}$
$E_{recycled}$		Resources consumed/emissions for the production process of the recycled material, including collection, sorting and transportation processes
$E_{recycling,EoL}$		Resources consumed/emissions for the recycling process at the EoL, including collection, sorting, transportation and recycled material production processes. In some cases, when technologies used are similar, $E_{recycled}$ can be similar to $E_{recycling,EoL}$
E_D		Resources consumed/emissions for disposal of waste material
E_D^{*}		Resources consumed/emissions for the disposal of waste material at the EoL of the material from which the recycled content is derived. (e.g. landfilling)
E_{ER}		Resources consumed/emissions for the energy recovery process.
E_{SE}		Avoided resources consumed/emissions for the specific substituted energy source
R_1	[Dimensionless]	"Recycled content of material" is the proportion of material input to the production process that has been recycled in a previous system ($0 \leq R_1 \leq 1$)
R_2		"Recyclability rate" is the proportion of the material in the product that will be recycled in a subsequent system (i.e. the rate between recycled output and virgin material input). R_2 takes into account any inefficiencies in the collection and recycling processes ($0 \leq R_2 \leq 1$)
R_3		The proportion of material in the product that is used for energy recovery (e.g. incineration with energy recovery) at EoL
LHV	[MJ/kg]	Lower Heating Value of the material in the product that is used for energy recovery.
X_{ER}		The efficiency of the energy recovery process (0 <XER <1) (i.e. the ratio between the energy content of output (e.g. output of electricity) and the energy content of the material in the product that is used for energy recovery).
K	[Dimensionless]	Ratio for any differences in quality between the secondary material and the primary material ("down-cycling"). $K = Q_S/Q_P$, where Q_S is the quality of the secondary material and Q_P the quality of the primary material.

Table B.3: Terms used in *PEF* method, Equation B.3

Different methods for allocation the end–of–life phase have been researched. A comparison between several allocation equations needs to be made in order to substantiate certain methods. Globally, there is two ways to go in the problem of comparing different materials regarding their complete life cycle.

1. Use one formula that fits the behaviour of all to be researched materials.

   In this way, comparison is easy and straightforward but it may not be possible to find (or construct) one formula that fits all purposes. Such an equation always is a simplified model for reality. However, with the use of a one–formula–fits–all approach, the same elements of all materials are left out of the equation, leaving the comparison fair.

2. Every material has its own EoL allocation equation, which suits the end–of–life characteristics of that specific material.

   In this way, the most realistic end–of–life approach for every material can be used. Comparison of different materials in this manner results in different elements being left out of the equation for different materials due to the modelling, which results in a less fair comparison. For this reason, the first approach is desired.

B.5 CONCLUSION LITERATURE STUDY

Interim conclusions can be drawn based on research question 1:

What is the influence of Design for Deconstruction on the environmental impact of a building?

- *How to implement the Design for Deconstruction concept into the LCA methodology?*

  It is chosen to implement the reuse and recycling percentages into the existing LCA method with the use of the Product Environmental Footprint method. As can be seen from Equation B.3, the *PEF* method uses a 50/50 allocation approach, similar to the 50/50 method of Nicholson in Figure B.2. The *PEF* method is a further developed and elaborated version of the LCA methodology, developed by Allacker et al. on behalf of the European Commission. It includes the same life cycle stages as the original LCA methodology, thus existing life cycle impact values from the Nationale MilieuDatabase (NMD) can still be used. The original *PEF* method does not include reuse by default, but this is included in section 4.4.

  In order to include DfD into the environmental impact calculation, the Building Circularity Index of Alba Concepts is used. The assumption that the Building Circularity Index (BCI) is directly related to the chance of a building being (partly) reused in the future is made. How this index is exactly incorporated is elaborated in section 4.4.

Although the *PEF* formula seems like an compelling option to use as a general EoL allocation equation, there are still some remarks to be placed.

- A Loss–of–Quality (LoQ) method (Concrete and timber) or a substitution method (steel) is preferred, instead of the existing 50/50 method. In that way, multiple life cycles can be taken into account instead of the maximum of 2 in a 50/50 allocation method. (50/50 allocation only considers previous/current or current/next cycle).

- Reuse is not taken into account by default. Design for Deconstruction is an important concept to include in this thesis, so this has to be included. The formula in its current state only accounts for recycling in the production and end–of–life phase. Next step is to include reuse (and thus DfD) in these life cycle phases as well.

In Appendix E, the *PEF* equation will be taken apart such that it can be compared to the C_5^n formula of steel and the loss of quality equation of concrete and timber allowing the aforementioned problems to be solved by adjusting the formula step–by–step.

C | BUILDING CIRCULARITY INDEX

Input
Generated
List value
Output

Materiaal	%virgin	%reuse	%recycle	%loss	TSL
Steel	0.4456	0.0448	0.5096	0	150
Concrete	0.98	0	0.02	0.2	150
Rebar	0.55	0	0.45	0.2	150
Sawn Timber	0.817	0.061	0.122	0	75
Glulam	1	0	0	0	75

Connection Type (CT)	Value
Clicked connection	1
Bolted connection	0.8
Pinned connection	0.6
Kitted connection	0.2
Welded Connection	0.1

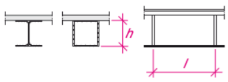
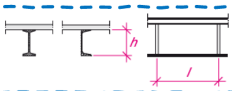
Connection Accessibility (CA)	Value
Accessible	1
Accessible extra actions without damage	0.8
Accessible extra actions repairable damage	0.6
Accessible extra actions irreparable damage	0.4
Inaccessible	0.1

Name	Parameter	Steel	Concrete	Rebar	Timber	Glulam
recycle rate	R2	0.91	0.8	0.95	0.1	0
reuse rate	R5	0.08	0	0	0.05	0
scrap to virgin rate	Y	0.56	0.025	0.56	1.22	0.13

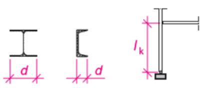
Figure C.1: Properties and parameters which are used for the BCI calculations.

D PRINCIPLES STRUCTURAL CALCULATION

D.1 RULES OF THUMB STEEL DESIGN

Constructie-element	Doorsnede en zijaanzicht	Afmeting van het element (h) in mm	Overspanning (ℓ) in m	Verhouding $\frac{h}{\ell}$
Breedflens-profielen of kokers		100–500	4–12	$\frac{1}{18}-\frac{1}{28}$
Profielstaal		200–500	6–30	$\frac{1}{15}-\frac{1}{20}$

(a) Steel beam rule of thumb.

Constructie-element	Doorsnede en zijaanzicht	Knik-lengte (ℓ_k) in m	Doorsnede-hoogte verhouding $\frac{d}{\ell_k}$	
Gewalst of gelast profiel		2–8	$\frac{1}{20}-\frac{1}{25}$	één bouwlaag
		2–4	$\frac{1}{7}-\frac{1}{18}$	meer bouwlagen

(b) Steel column rule of thumb.

Figure D.1: Steel framework rules of thumb according to Jellema: [Hofkes et al., 2004]

q_k [kN/m2]	Span [m] 16	12,6	10,8	9	7,2	6,3	5,4	3,6
5	400	320	320	200	200	200	150	150
10	NaN	400	320	320	200	200	200	150
15	NaN	NaN	400	320	320	320	200	150
20	NaN	NaN	400	400	320	320	320	200

(a) Hollow–core slab thickness rule of thumb.

q_k [kN/m2]	Span [m] 16	12,6	10,8	9	7,2	6,3	5,4	3,6
5	490	429	429	308	308	308	268	268
10	NaN	490	429	429	308	308	308	268
15	NaN	NaN	490	429	429	429	308	268
20	NaN	NaN	490	490	429	429	429	308

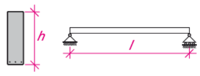
(b) Hollow–core slab weight rule of thumb.

q_k [kN/m2]	Span [m] 16	12,6	10,8	9	7,2	6,3	5,4	3,6
5	NaN	12,194	5,538	4,849	2,86	1,95	1,82	1,04
10	NaN	12,194	6,487	5,538	2,99	2,86	1,95	1,3
15	NaN	10,374	9,906	8,996	4,849	4,16	2,86	1,82
20	NaN	NaN	10,374	7,176	5,538	3,9	4,16	2,08

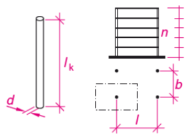
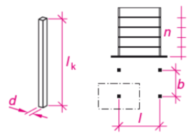
(c) Hollow–core slab rebar amount rule of thumb.

Figure D.2: Rules of thumb regarding VBI hollow–core slabs, according to BHH model: [Westenbrugge-Bilardie and Peters, 2016]. The selected dimension for the case–study is shown in blue.

D.2 RULES OF THUMB CONCRETE DESIGN

Constructie-element	Doorsnede en aanzicht	Overspanning ℓ in m	Verhouding $\frac{h}{\ell}$	Verhouding $\frac{b}{h}$
Ligger ter plaatse gestort		4–18	$\frac{1}{10}$	$\frac{1}{3}-\frac{1}{5}$

(a) Concrete beam rule of thumb.

Constructie-element	Aanzicht kolom en plattegrond gebouw		Verhouding $\frac{b}{\ell_k}$	Verhouding $\frac{d}{\ell_k}$
Ronde kolom		ter plaatse gestort beton	1	$\frac{1}{25}\sqrt{n}$
			$\frac{1}{2}$	$\frac{1}{35}-\frac{1}{40}\sqrt{n}$
		prefab-beton	1	$\frac{1}{30}-\frac{1}{35}\sqrt{n}$
			$\frac{1}{2}$	$\frac{1}{45}-\frac{1}{55}\sqrt{n}$
Vierkante kolom		ter plaatse gestort beton	1	$\frac{1}{25}-\frac{1}{35}\sqrt{n}$
			$\frac{1}{2}$	$\frac{1}{40}-\frac{1}{50}\sqrt{n}$
		prefab-beton	1	$\frac{1}{35}-\frac{1}{45}\sqrt{n}$
			$\frac{1}{2}$	$\frac{1}{55}-\frac{1}{65}\sqrt{n}$
$\ell \leq 4$m				

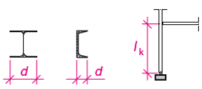
(b) Concrete column rule of thumb.

Figure D.3: Concrete framework rules of thumb according to Jellema: [Hofkes et al., 2004]

D.3 RULES OF THUMB TIMBER DESIGN

Constructie-element	Doorsnede en zijaanzicht	Over-span-ning ℓ in m	Verhou-ding $\frac{b}{h}$	Verhou-ding $\frac{b}{a}$	Verhou-ding $\frac{h}{\ell}$	H.o.h.-afstand a in m
Massieve ligger		2,5–8	$\frac{1}{3}$	–	$\frac{1}{15}-\frac{1}{20}$	–
Gelamineerde ligger		6–25	$\frac{1}{6}-\frac{1}{10}$	$\frac{1}{17}-\frac{1}{20}$	$\frac{1}{20}$	$\frac{\ell}{2}$ $\frac{\ell}{3}$

(a) Timber beam rule of thumb.

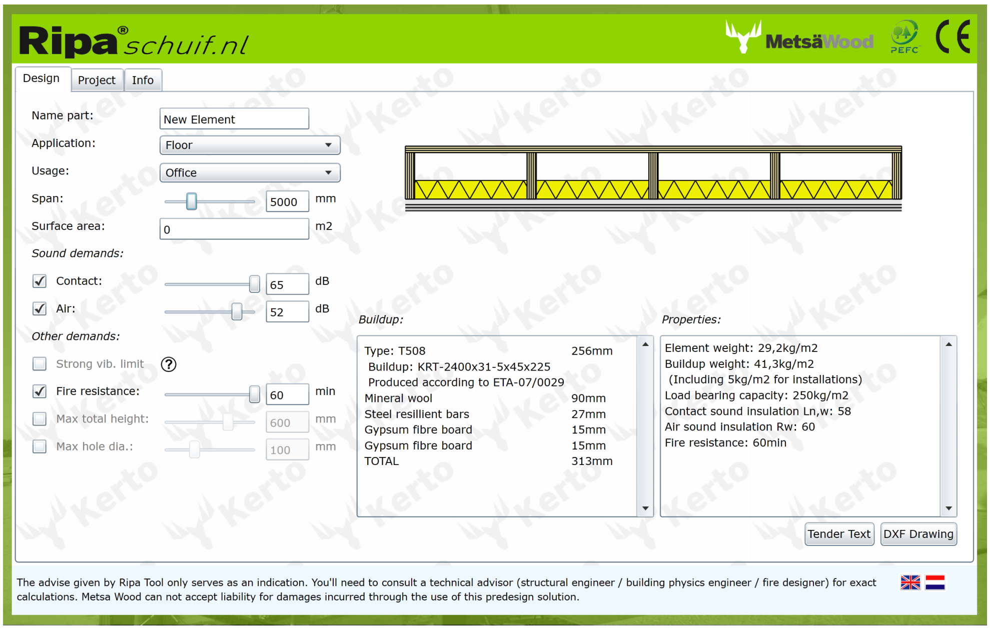
Constructie-element	Doorsnede en zijaanzicht	Knik-lengte (ℓ_k) in m	Doorsnede-hoogte verhouding $\frac{d}{\ell_k}$	
Gewalst of gelast profiel		2–8	$\frac{1}{20}-\frac{1}{25}$	één bouwlaag
		2–4	$\frac{1}{7}-\frac{1}{18}$	meer bouwlagen

(b) Timber column rule of thumb.

Figure D.4: Timber framework rules of thumb according to Jellema: [Hofkes et al., 2004]

hoogte in mm	aantal lamellen	breedte in mm				
		42	56	66	90	115
90	2					
115	2 1/2					
135	3					
180	4					
225	5					
270	6					
315	7					
360	8					
405	9					
450	10					
495	11					
540	12					
630	14					

Figure D.5: Standard dimensions of glued laminated timber, according to Jellema: [Hofkes et al., 2004].



(a) Ripa Schuif rule of thumb dimensioning program. The floor buildup as shown here is used throughout the research.

	Span [m]							
	12	11	10	9	8	7	6	5
Floor height [mm]	683	583	533	483	443	383	343	313
Floor weight [kN/m2]	0.7	0.542	0.474	0.412	0.363	0.332	0.311	0.292
Buildup weighth [kN/m2]	0.413	0.413	0.413	0.413	0.413	0.413	0.413	0.413
Roof height [mm]	350	290	275	250	230	200	200	200
Roof weight [kN/m2]	0.341	0.324	0.32	0.312	0.307	0.298	0.298	0.298

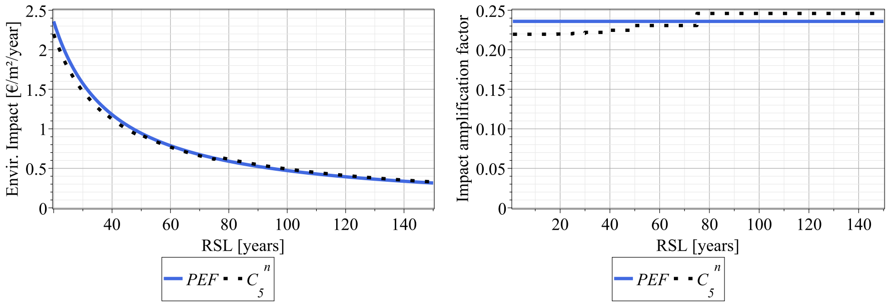
(b) Results of the Ripa Schuif tool regarding corresponding to different spans.

Figure D.6: Timber hollow–core slab "Metsawood Kerto Ripa" dimensions according to [Kennisbank Biobased Bouwen, 2019; Metsa Wood UK, 2019]

E PEF EQUATIONS AND MODIFICATION

E.0.1 Comparison and adaptation from PEF (50/50 method) to C_5^n (substitution method)

In order to make a considered choice for the most fitting allocation formula, different formulas have been considered, constructed and compared. First, the original PEF formula has been compared to the C_5^n formula used for steel. This formula is a substitution allocation method, which is the preferred method for steel allocation. For this reason, modification from PEF to C_5^n is tried first. As the purpose of this report is to show the progress of the research including the steps taken, this comparison is written down. However in the end, the modification to this method is not deemed possible, so the next option was taken, which is described in subsection E.0.2. For this reason, the comparison and modification of PEF to C_5^n is not described extensively but only briefly. In these comparisons, energy recovery of the PEF equation is not taken into account.



(a) Normalized PEF and C_5^n equations (multiplied by χ) **(b)** Non–normalized equations (divided by χ)

Figure E.1: Comparison of PEF and C_5^n equations

$$\chi = \frac{m}{GFA \cdot RSL} \tag{E.1}$$

with:

m = total mass of the material in the building

GFA = Gross Floor Area of the building

RSL = The service life of the building

$$C_5^n = \chi \left[\frac{(1-R_1)E_v + (R_1 - R_1^{n_f+1})E_{recycled}}{1 - R_1^{n_f+1}} \right] \tag{E.2}$$

Figure E.1 shows the comparison of the original PEF formula stated and separated in the previous section and the most promising allocation method for steel, the C_5^n method elaborated in section B.2, shown in Equation E.2. Both these equations do not take reuse of elements into account, only recycling is considered. Figure E.1a shows the complete formula in such a way that the allocation is normalized by a normalization factor in order to compare different buildings. The normalization factor χ is stated in Equation E.1. This factor is left out of the equation in Figure E.1b, so that only the amplification factor is left. This shows the small difference in approach of the two equations. Where the original *PEF* equation has a constant amplification over time, the C_5^n equation shows an increasing amplification, due to the number of material life cycles n_f appearing in the formula. Nevertheless, both equations shown a similar environmental impact, which is to be expected. The remaining material life time is not taken into account in the *PEF* equation, which it should if material reuse is considered.

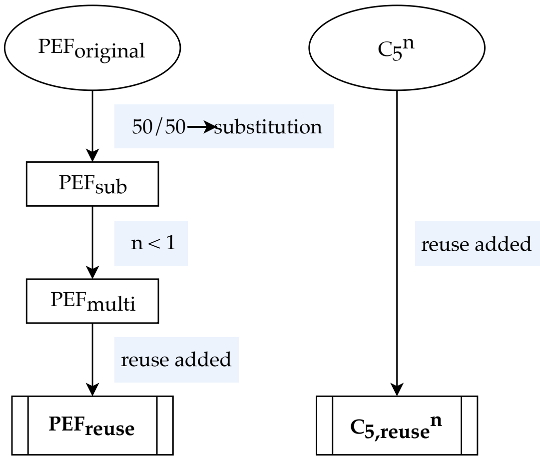


Figure E.2: Modification of the original *PEF* equation to an equation with the required elements added with a change of allocation method from 50/50 to substitution

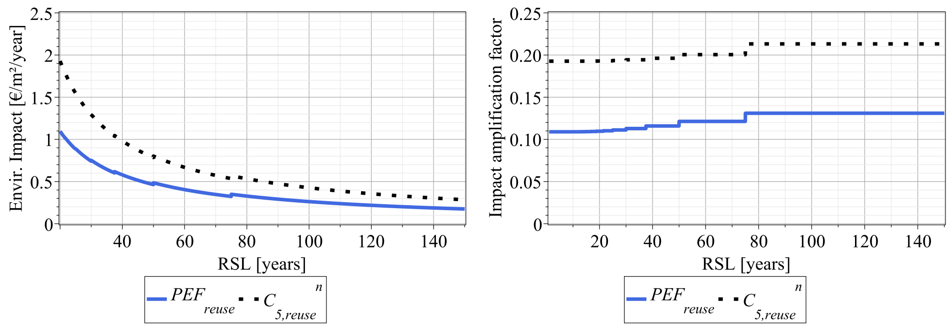
$$PEF_{reuse} = \chi \left[\frac{S_1}{2 - R_1 - R_2 - R_4 - R_5} \right] \tag{E.3a}$$

$$C^n_{5,reuse} = \chi \left[\frac{S_2}{1 - R_1^{n_f+1} - R_4^{n_f+1}} \right] \tag{E.3b}$$

with:

$$R_1 = \text{Recycled content (input)}$$
$$R_2 = \text{Recycling rate (output)}$$
$$R_4 = \text{Reused content (input)}$$
$$R_5 = \text{Reusing rate (output)}$$
$$\begin{aligned} S_1 = &(1 - R_1 - R_4)E_v + (R_1 - R_1^{n_f+1})E_{recycled} + R_4 E_{reused} \\ &+ (R_2 - R_2^{n_f+1})(E_{recycling,EoL} - E_v^* K) + R_5(E_{reusing,EoL} - E_v^*) \\ &+ (1 - R_2 - R_5)E_D - (R_1 - R_1^{n_f+1})E_D^* - R_4 E_D^* \end{aligned}$$
$$S_2 = (1 - R_1 - R_4)E_v + (R_1 - R_1^{n_f+1})E_{recycled} + (R_4 - R_4^{n_f+1})E_{reused}$$

Reuse is not taken into account in both original *PEF* and C_5^n methods, so while adapting $PEF_{original}$ into a substitution allocation equation, both methods are modified to include a reuse component. The transition from the original to the modified formula is visualized in Figure E.2. This transition results in the equations of Equation E.3a and E.3b.



(a) Normalized PEF and C_5^n equations (including χ)

(b) Non–normalized equations (divided by χ)

Figure E.3: Comparison of the adapted PEF_{reuse} and $C^n_{5,reuse}$ equations

While the difference in the original equations is negligible, the differences here are more pronounced. The amplification factors (the parts between the square brackets in Figure E.3a and E.3b) shown in Figure E.3b differentiate significantly by default, which shows that changing the PEF from a 50/50 to a substitution allocation method drastically changes the perceived environmental impact. This is not a desirable effect. In addition, modification of this equation from a general one into a custom equation necessary for the scenarios described in subsection 4.4.2 proved to be not possible as well. Due to these negative factors of importance, a different path is chosen.

E.0.2 Adaptation PEF as a 50/50 allocation method

In order to meet the requirements for the allocation formula set in the multi–criteria table of Table 4.1 summarized in section B.5, the PEF formula is not adjusted to a substitution method, but is retained by the original 50/50 method. The original PEF is modified to include the loss of quality (factor K) and reuse conditions. The adaptation from the original to the new equation is schematized in Figure E.4. As can be seen, the original equation is first adapted to include the reuse component. After this, the factor of remaining service life is incorporated. After this, different loss of quality approaches are compared and in the end, the chosen equations with the desired effect are assembled into one equation which fits all requirements.

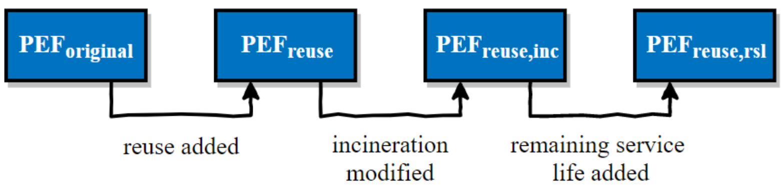


Figure E.4: Modification of the original PEF equation to an equation with the required elements added

Including the reuse component

Equation E.4 shows how the reuse component in incorporated into the existing original PEF allocation equation. The boxed parts of the equation show the modifications. Reuse is taken into account the same way as recycling is taken care of in the original equation. The small changes are the loss of quality factor K, which is now divided into a Loss–of–Quality (LoQ) factor for recycling and for reuse, K_{rec} and K_{reu} respectively. The result of these modifications are visualized in Figure E.5. Figure E.5b clearly shows the reduction in amplification of the environmental impact due to reuse being added. The reduction is constant during the total service life considered. This means, the credits earned to the current building due to materials being reused in the next building are always the same value, even though the technical service life of the material can be almost expired and reuse is not a realistic option anymore. This is the disadvantage of the 50/50 allocation method used. The allocation is always 50/50, no matter what service life is left. In order to allow for this matter, the remaining service life component is added in the next section.

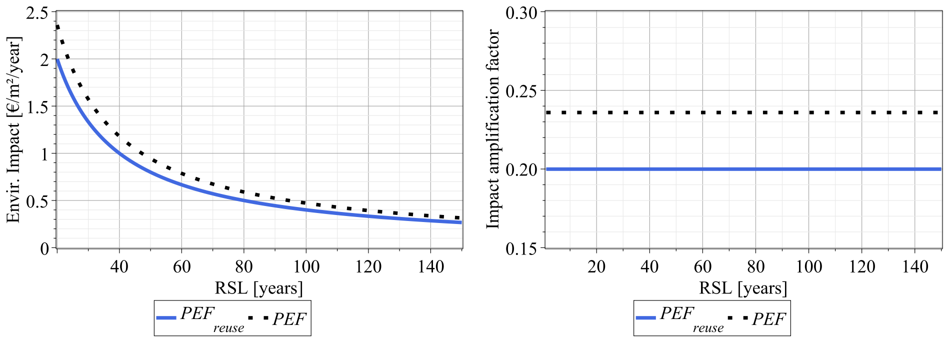
$$\begin{aligned} PEF_{reuse} = \quad & \chi \Bigg[\left(1 - \frac{R_1}{2} - \boxed{\frac{R_4}{2}}\right) E_v + \frac{R_1}{2} E_{recycled} + \boxed{\frac{R_4}{2} E_{reused}} \\ & + \frac{R_2}{2} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) + \boxed{\frac{R_5}{2} \left(E_{reusing,EoL} - E_v^* K_{reu}\right)} \\ & + \left(1 - \frac{R_2}{2} - R_3 - \boxed{\frac{R_5}{2}}\right) E_D \\ & + R_3 \left(E_{ER} - LHV \left(X_{ER,heat} \cdot E_{SE,heat} + X_{ER,elec} \cdot E_{SE,elec}\right)\right) \\ & - \frac{R_1}{2} E_D^* - \boxed{\frac{R_4}{2} E_D^*} \Bigg] \end{aligned} \tag{E.4}$$

with:

$\boxed{eq.}$ = Modified part of equation for the purpose of adding reuse

K_{rec} = Ratio for any differences in quality between the secondary and primary material when the material is recycled. (Downcycling ratio)

K_{reu} = Ratio for any differences in quality between the secondary and primary material when the material is reused. (Downcycling ratio is bigger in the recycling process, but apparent in reuse as well)



(a) Normalized equations (including χ)

(b) Non–normalized equations (divided by χ)

Figure E.5: Comparison of the original *PEF* and the modified equation to include reuse

Adapting block D: Incineration
Block D of the separated *PEF* equation (Figure 4.5) is adjusted in order to comply with the Nationale MilieuDatabase (NMD). Which means the parameters necessary to calculate the avoided impact of the substituted energy production are switched from plant specific parameters ($X_{ER,heat}, X_{ER,elec}, E_{SE,heat}, E_{SE,elec}$) to general parameters applicable for the Dutch energy production. The result is shown in Equation E.5. The result is a comprehensive equation with only parameters which are stated in the NMD.

$$\begin{aligned}
PEF_{reuse,inc} = \ & \chi \Bigg[\left(1 - \frac{R_1}{2} - \frac{R_4}{2}\right) E_v + \frac{R_1}{2} E_{recycled} + \frac{R_4}{2} E_{reused} \\
& + \frac{R_2}{2}\left(E_{recycling,EoL} - E_v^* K_{rec}\right) + \frac{R_5}{2}\left(E_{reusing,EoL} - E_v^* K_{reu}\right) \\
& + \left(1 - \frac{R_2}{2} - R_3 - \frac{R_5}{2}\right) E_D \\
& + \boxed{R_3 \left(E_{ER} - LHV\left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right)} \\
& - \frac{R_1}{2} E_D^* - \frac{R_4}{2} E_D^* \Bigg]
\end{aligned} \tag{E.5}$$

with:

$\boxed{eq.}$ = Modified incineration part of equation
$E_{SE,r}$ = Avoided renewable energy production emissions
$E_{SE,f}$ = Avoided fossil energy production emissions
LHV = Lower Heating Value of the material incinerated
R_r = Percentage of the total energy produced in the Netherlands coming from renewable resources
R_f = Percentage of the total energy produced in the Netherlands coming from fossil resources

Adding the remaining service life component
The remaining service life factor is incorporated in order to able fair comparison of different materials based on their technical service life. This modification is separated in two parts:

1. Incorporating the remaining service life as a factor for the inclusion of negative credits due to possible future reuse, stated as $(1 - n)$. This factor is only applied at the reuse component at the end–of–life of the material (output side). Structural element reuse at the input side is not modified for remaining service life. This is due to the uncertain character of the remaining service life from reused elements from a previous life cycle.

2. Incorporating the possibility of the building outliving the construction material, which can be stated as $TSL < RSL$. this factor is stated as n_c and can be described as the round up value of the reference service life of the building divided by the technical service life of the construction material.

$$
\begin{aligned}
PEF_{reuse,rsl} = \quad & \chi \Bigg[\left(1 - \frac{R_1}{2} - \frac{R_4}{2}\right) \boxed{E_v n_c} + \frac{R_1}{2} E_{recycled} + \frac{R_4}{2} E_{reused} \\
& + \frac{R_2}{2} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + \boxed{R_5 \left(n E_{reusing,EoL} - (1-n) E_v^* K_{reu}\right)} \\
& + \left(1 - \frac{R_2}{2} - R_3 - \boxed{(1-n) R_5}\right) \boxed{E_D n_c} \\
& + R_3 \left(E_{ER} - LHV \left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \frac{R_1}{2} E_D^* - \frac{R_4}{2} E_D^* \Bigg]
\end{aligned} \tag{E.6}
$$

with:

$\boxed{eq.}$ = Modified part of equation for the purpose of adding the remaining service life component.

$(1-n)$ = Factor to include a partly credit due to the TSL of the material remaining. Derived as shown in Figure E.6.

$$n = \frac{\text{Reference Service Life}}{\text{Technical Service Life}}$$

$$n_c = \left\lceil \frac{\text{Technical Service Life}}{\text{Reference Service Life}} \right\rceil$$

Number of times new material new virgin material is needed in order to comply to the RSL, in case of $TSL < RSL$.

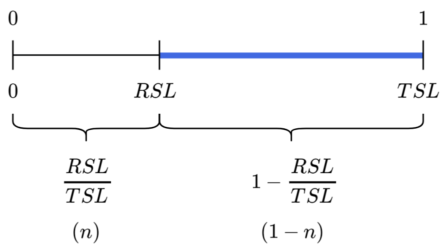
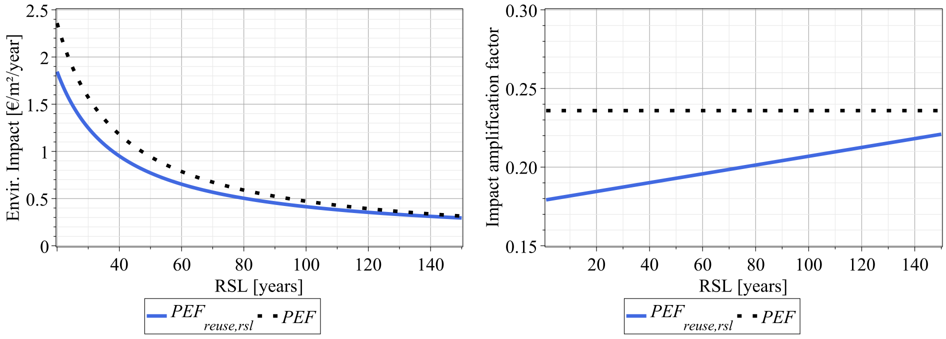


Figure E.6: Derivation of the $(1-n)$ factor of Equation E.6, where the ratio between the Reference Service Life of a building and the Technical Service Life of a material is normalized from $0 - TSL$ to $0 - 1$.



(a) Normalized equations (including χ)

(b) Non–normalized equations (divided by χ)

Figure E.7: Comparison of the original PEF and the adapted equation to include reuse

The required modifications listed above are implemented as indicated in Equation E.6 by the boxed parts of the equation. The result of these modifications are visualized in Figure E.7. Instead of the constant reduction in amplification, Figure E.7b shows a linearly decreasing reduction in amplification. This change in behaviour is due to the remaining service life factor $(1 - n)$ and service life factor n, which are directly related to the reference service life. The rate of decrease is dependant on the reuse percentages and impact values entered, which differ per material. The derivation of factor $(1 - n)$ is shown in Figure E.6, where the timeline of $[0 - TSL\rangle$ is normalized to $[0 - 1\rangle$, which result in the remaining service life factor being $(1 - \frac{RSL}{TSL})$.

Equation E.6 is mostly changed in the reuse part, which includes the part of R_5. In this part, $E_{reusing,EoL}$ is divided by 2, while the $E_v^* K_{reu}$ part is multiplied by $(1 - n)$. The reason that the first part is divided by 2 and the second part is not, is due to the credits system being used. The second part, $(1 - n)E_v^* K_{reu}$, is considering the credits being given due to the avoided primary material production in the next life cycle, due to reusing materials. The remaining service life of this to be reused material is known and taken into account. The service life remaining from the material of the first part is not known, due to previous material life cycle is not always known. In that case, the standard allocation of the 50/50 method is used.
At the disposal side of the equation, the $\frac{R_5}{2}$ part is modified into $(1 - n)R_5$ in order to accomodat for the remaining service life.

Summarized equations
To sum it up, all steps of the modification are shown in Figure E.8 and E.9, with the final equation in blue, $PEF_{reuse,rsl}$. In this case, the modified equation starts at a lower impact, but gradually approaches the original equation, due to the reuse not being able at the end of the material service life.

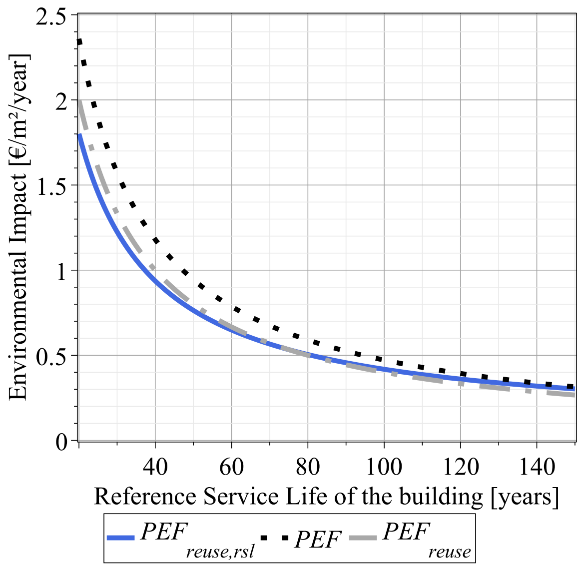


Figure E.8: Comparison of all modified *PEF* equations using 50/50 allocation

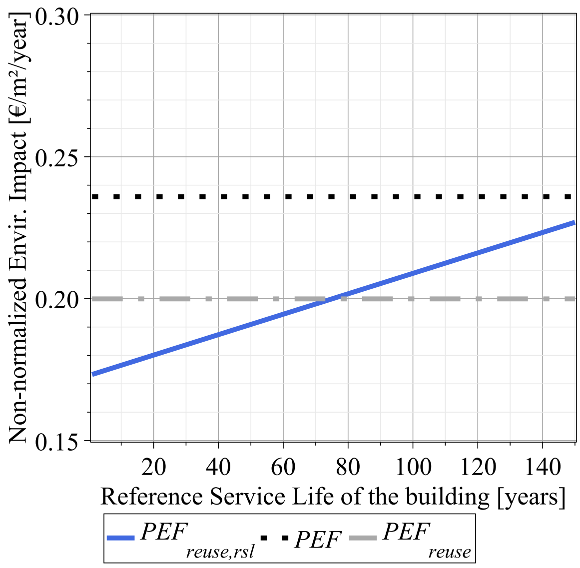


Figure E.9: Comparison of all modified Non–normalized *PEF* equations (divided by χ) using 50/50 allocation

E.1 END–OF–LIFE EQUATIONS PER SCENARIO

Equation E.6 is meant as an equation with mean values. The equation is split into two parts, input and output. Input can be seen as the Product and Construction stage and output as the End–of–Life and Beyond–End–of–Life stage of the decision tree. This compact form is visualized in Figure E.10. This flowchart gives a total of $\# \, input \times \# \, output = 3 \times 2 = 6$ scenarios. The general allocation equation of subsection E.0.2 is modified for each scenario in the next section.

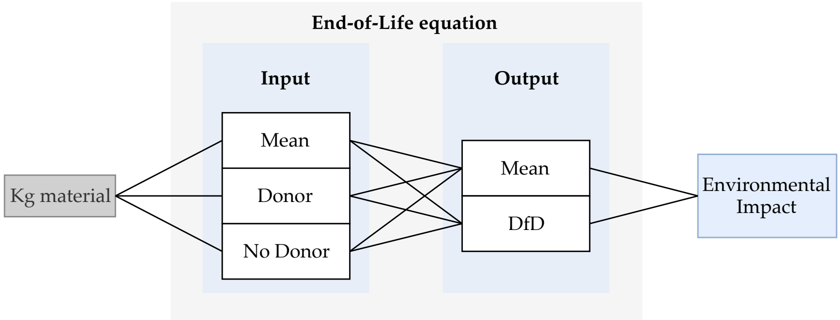


Figure E.10: Compact form of scenarios. End–of–Life equations per scenario are based on the six scenarios of this flowchart.

Input

- *Average:* The average values for the input side of the equation are adopted from the outcome of the literature review with regard to recycling and reuse rates. This option is chosen in case of a general first calculation of building, when options for Design for Deconstruction are not considered yet.
- *Donor:* This option is chosen if a donor structural framework is opted. The structural elements of an old building are reused in the to be built structure.
- *No Donor:* This option is chosen if no donor structural framework is opted. The difference of this option and [*Mean*] is this option does not include reuse at all, so also no mean values.

Output

- *Average:* The average values for the output side of the equation are adopted from the outcome of the literature review with regard to recycling and reuse rates. This option is chosen in case of a general first calculation of building, when it is not decided yet if the building has to be able to be deconstructed in the future or not.
- *DfD:* This option is chosen if detailed requirements regarding Design for Deconstruction are considered. That is, the chance that a certain designed building is to be deconstructed and reused for a second life cycle is included in the sustainability calculation. This option needs several extra input arguments regarding the Building Circularity Index (subsection 4.2.3) such as, structural joint types and the accessibility of these joints.

The following scenarios are specified as **Scenario #: Input — Output**

E.1.1 Scenario 1: Average — Average

The standard equation of Equation E.6 is used.

$$
\begin{aligned}
E_{Avg-Avg} = \chi \Bigg[& \left(1 - \frac{R_1}{2} - \frac{R_4}{2}\right) E_v n_c + \frac{R_1}{2} E_{recycled} + \frac{R_4}{2} E_{reused} \\
& + \frac{R_2}{2}\left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + R_5\left(n E_{reusing,EoL} - (1-n) E_v^* K_{reu}\right) \\
& + \left(1 - \frac{R_2}{2} - R_3 - (1-n) R_5\right) E_D n_c \\
& + R_3\left(E_{ER} - LHV\left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \frac{R_1}{2} E_D^* - \frac{R_4}{2} E_D^* \Bigg]
\end{aligned} \tag{E.7}
$$

E.1.2 Scenario 2: Donor — Average

In this scenario, the input part of the general equations is modified in order to accommodate for the use a donor structural framework for reused elements, which is called Design for Deconstruction at input side. The original reuse rate at input R_4 is switched for P_{r4} and the recycling rate is taken of the remainder $R_1(1-P_{r4})$.

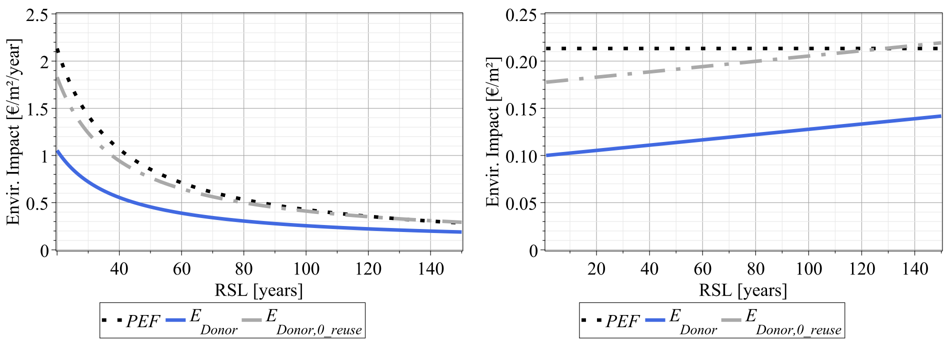
$$
\begin{aligned}
E_{Donor-Avg} = \quad & \chi \Bigg[\left(1 - \boxed{\frac{R_1(1-P_{r4})}{2} - \frac{P_{r4}}{2}}\right) E_v n_c \\
& + \boxed{\frac{R_1(1-Pr4)}{2} E_{recycled} + \frac{P_{r4}}{2} E_{reused}} \\
& + \frac{R_2}{2}\left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + R_5\left(n E_{reusing,EoL} - (1-n) E_v^* K_{reu}\right) \\
& + \left(1 - \frac{R_2}{2} - R_3 - (1-n) R_5\right) E_D n_c \\
& + R_3\left(E_{ER} - LHV\left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \boxed{\frac{R_1(1-P_{r4})}{2} E_D^* - \frac{P_{r4}}{2} E_D^*} \Bigg]
\end{aligned} \tag{E.8}
$$

With:

$P_{r4} =$ Percentage the load–bearing structure what is constructed out of reused elements. (% DfD at input side)

E.1.2.1 *Validation of Scenario 2*

When scenario 2: E_{Donor} is compared with the original *PEF* equation in Figure E.11b, it is noticeable that E_{Donor} is constantly rising, but always results in a lower impact. The lower overall impact is the due to the reuse of structural elements (Donor structural framework). When the reuse percentage is set to 0 % (see $E_{Donor,0reuse}$), the environmental impact roughly corresponds to the impact of the original *PEF* equation. The oblique line is the result of the factor n, which is also included in the generally validated Equation 4.8.



(a) Equations including χ

(b) Non–normalized equations (divided by χ)

Figure E.11: Comparison of scenario 2: E_{Donor} with the original PEF equation and E_{Donor} with reuse (P_{r5}) set to 0%.

E.1.3 Scenario 3: Average — DfD

The output part of the standard equation is modified in order to allow for the option of Design for Deconstruction in the equation. This is done using the Building Circularity Index of subsection 4.2.3. The default value for reuse at the end–of–life R_5 is switched for a project dependent value, calculated by $P_r \cdot BCI$. This value can be stated as the percentage of the load bearing structure that is being reused in the future times the chance that the existing structure is being reused at all. The boxed parts of the equation are the adapted parts for the Design for Deconstruction (DfD) output scenario.

$$
\begin{aligned}
E_{Avg-DfD} = \quad & \chi \Bigg[\left(1 - \frac{R_1}{2} - \frac{R_4}{2}\right) E_v n_c + \frac{R_1}{2} E_{recycled} + \frac{R_4}{2} E_{reused} \\
& + \boxed{\frac{R_2(1 - P_{r5}BCI)}{2}} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + \boxed{P_{r5} \cdot BCI} \left(n E_{reusing,EoL} - (1-n) E_v^* K_{reu}\right) \\
& + \Bigg(1 - \boxed{\frac{R_2}{2}(1 - P_{r5}BCI) - R_3(1 - P_{r5}BCI)} \\
& - \boxed{(1-n) P_{r5} BCI} \Bigg) E_D n_c \\
& + \boxed{(1 - P_{r5} \cdot BCI) R_3} \left(E_{ER} - LHV \left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \frac{R_1}{2} E_D^* - \frac{R_4}{2} E_D^* \Bigg]
\end{aligned}
\tag{E.9}
$$

With:

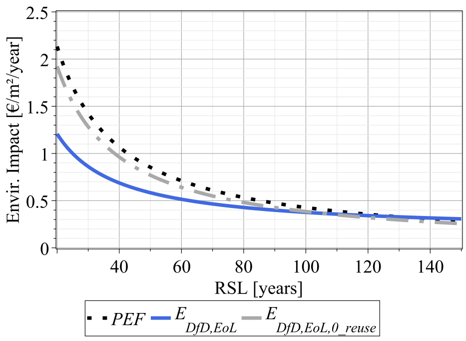
$\boxed{eq.}$ = Modified part of equation

P_{r5} = Percentage of the load bearing structure what is being reused in case of DfD in the future. (% DfD at output side)

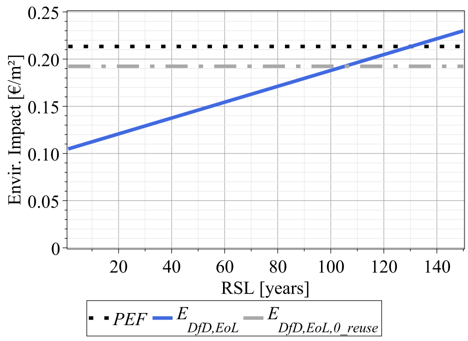
BCI = Building Circularity Index (chance of the existing structure being used as a donor structural framework in the future).

E.1.3.1 *Validation of Scenario 3*

When scenario 3: E_{DfD} is compared with the original PEF equation in Figure E.12b, it is noticeable that E_{DfD} is constantly rising and after 120 years surpassing the environmental impact of the original PEF equation. The lower overall impact is the due to the reuse of structural elements; a small standard amount of reuse is taken into account. When the reuse percentage is set to 0 % (see $E_{DfD,0reuse}$), the environmental impact roughly corresponds to the impact of the original PEF equation. The DfD scenario does what it is expected to do; at short lifespans of the building the impact is low, due to the high reuse potential of the materials (they still have a long technical service life left). When long lifespans are concerned, the environmental impact becomes higher than the standard scenario because there is no reuse potential left in the material.



(a) Equations including χ



(b) Non–normalized equations (divided by χ)

Figure E.12: Comparison of scenario 3: E_{DfD} with the original PEF equation and E_{DfD} with reuse (P_{r4}) set to 0%.

E.1.4 Scenario 4: Donor — DfD

Scenario 2 and 3 are combined in scenario 4, which has DfD included in both the input and output stage. This means modifications in comparison to scenario 1 are in both the input and output stage, as shown by the boxed parts of Equation E.10.

$$
\begin{aligned}
E_{Donor-DfD} = \chi \Bigg[& \left(1 - \boxed{\frac{R_1(1-P_{r4})}{2} - \frac{P_{r4}}{2}}\right) E_v n_c \\
& + \boxed{\frac{R_1(1-Pr4)}{2} E_{recycled} + \frac{P_{r4}}{2} E_{reused}} \\
& + \boxed{\frac{R_2(1-P_{r5}BCI)}{2}} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + \boxed{P_{r5}BCI} \left(nE_{reusing,EoL} - (1-n)E_v^* K_{reu}\right) \\
& + \left(1 - \boxed{\frac{R_2}{2}(1-P_{r5}BCI) - R_3(1-P_{r5}BCI)}\right. \\
& - \left.\boxed{(1-n)P_{r5}BCI}\right) E_D n_c \\
& + \boxed{(1-P_{r5} \cdot BCI)R_3} \left(E_{ER} - LHV\left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \boxed{\frac{R_1(1-P_{r4})}{2} E_D^* - \frac{P_{r4}}{2} E_D^*} \Bigg]
\end{aligned}
\tag{E.10}
$$

E.1.5 Scenario 5: No Donor — Average

Scenario 5 is chosen if the user is sure that no reused elements are used to construct the building, but no specific building method is chosen, so the chance of DfD in the future (Building Circularity Index (BCI)) is not known yet. This means the reuse percentages are taken out of the equation at input side, and the output side is kept the same as scenario 1.

$$
\begin{aligned}
E_{No\ Donor-Avg} = \chi \Bigg[& \left(1 - \frac{R_1}{2}\right) E_v n_c + \frac{R_1}{2} E_{recycled} \\
& + \frac{R_2}{2} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + R_5 \left(nE_{reusing,EoL} - (1-n)E_v^* K_{reu}\right) \\
& + \left(1 - \frac{R_2}{2} - R_3 - (1-n)R_5\right) E_D n_c \\
& + R_3 \left(E_{ER} - LHV\left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \frac{R_1}{2} E_D^* \Bigg]
\end{aligned}
\tag{E.11}
$$

E.1.6 Scenario 6: No Donor — DfD

Lastly, scenario 6 contains the option if no reused elements are used for the construction of the building, but the option for DfD in the future is opted for. This results in no DfD input side and DfD by means of the BCI factor at output side, as shown in Equation E.12.

$$
\begin{aligned}
E_{No\ Donor-DfD} = \chi \Bigg[& \left(1 - \frac{R_1}{2}\right) E_v n_c + \frac{R_1}{2} E_{recycled} \\
& + \boxed{\frac{R_2(1 - P_{r5}BCI)}{2}} \left(E_{recycling,EoL} - E_v^* K_{rec}\right) \\
& + \boxed{P_{r5}BCI} \left(nE_{reusing,EoL} - (1-n)E_v^* K_{reu}\right) \\
& + \Bigg(1 - \boxed{\frac{R_2}{2}(1 - P_{r5}BCI) - R_3(1 - P_{r5}BCI)} \\
& - \boxed{(1-n)P_{r5}BCI} \Bigg) E_D n_c \\
& + \boxed{(1 - P_{r5} \cdot BCI)R_3} \left(E_{ER} - LHV \left(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f}\right)\right) \\
& - \frac{R_1}{2} E_D^* \Bigg]
\end{aligned}
\tag{E.12}
$$

E.1.7 Scenario specific equations compared

All different equations are compared in Figure E.13 and especially E.14. Here, the difference between the general equation (scenario 1) in blue, and the several specified equations of Scenario 2 – 6 in grey are shown. Scenario 1, $E_{Avg-Avg}$, is acting as a reference equation.

Considering $E_{Avg-DfD}$, it can be seen that using Design for Deconstruction in the output stage only is beneficial when using a shorter Reference Service Life, which is to be expected. If longer service lives are used, the material is not longer suitable for future reuse, so the benefit is gone.

When $E_{Donor-Avg}$ is considered, it can be seen that a constant lower environmental impact over the service life is achieved. The constant character of this difference between $E_{Donor-Avg}$ and $E_{Avg-Avg}$ is because the Design for Deconstruction at input (use of donor structural framework) does not take the service life of the building into account. This is due to the fact that the remaining service life from the donor structural framework is not always known, so the safe approach is taken.

$E_{Donor-DfD}$ combines both aforementioned equations, which result can be seen Figure E.14. The combination of using DfD as input and output, gives the lowest environmental impact when a short RSL is considered, but surpasses $E_{Donor-Avg}$ in longer service lives, due to that equation not taking the RSL into account in its equation.

When looking at both equations which do not taken reuse as input, $E_{No\ Donor-Avg}$ and $E_{No\ Donor-DfD}$, a higher environmental impact than all other approaches are found. It can be stated that taking DfD into account significantly reduces the impact calculated and explicitly not using DfD significantly increases the impact calculated.

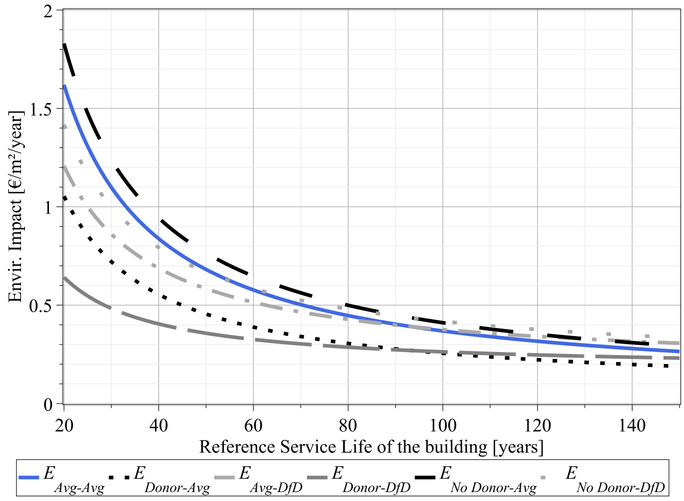


Figure E.13: Comparison of all scenario specific allocation equations

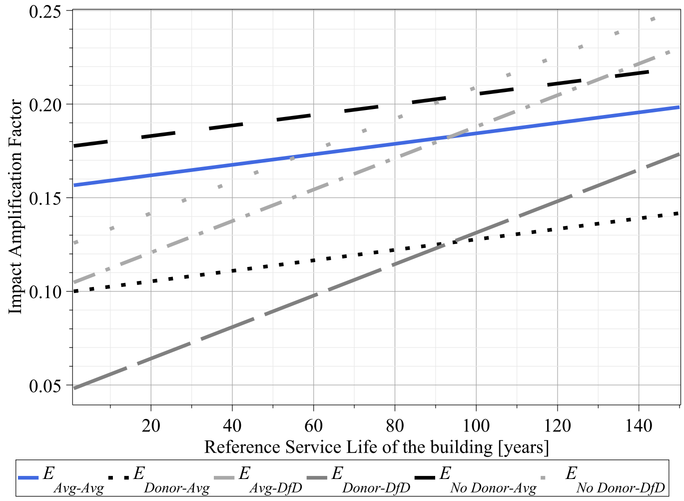


Figure E.14: Comparison of all non–normalized scenario specific allocation equations

F ENVIRONMENTAL IMPACT PARAMETERS

F.1 ENVIRONMENTAL IMPACT PARAMETERS STRUCTURAL STEEL

The parameters of Table 4.3 need to be specified for every material. In this section, the specific parameters for steel will be discussed. subsection F.1.1 includes the general parameters such as recycled and reused content, while subsection F.1.2, F.1.3 and F.1.4 delve deeper into the virgin, recycling and reusing material impact respectively. At last, subsection F.1.5 discusses the impact of phase C of Figure 4.2, the end–of–life phase.

F.1.1 General material–related parameters

The reuse and recycle percentages of steel are investigated. According to C. Thormark in [Thormark, 2009], the percentages of three main scenarios of steel waste in Norway are prescribed. In this research however, three main input scenarios and two main output scenarios are used. Mean values for these reuse and recycle rates as for the relative environmental impact of those actions need to be found. The reuse and recycle rates of the UK in the last years are summarized by Cullen and Drewniok in Table F.1. The lower row represents the mean values of the percentages of reuse, recycle and landfill. These percentages are used further down this research. The recycling rate at output is found using the future production rate.

For the calculation of these mean values, the Milieu Relevante Product Informatie (MRPI) values are not taken into account, due to their misleading nature. The 49% reuse value includes both reuse on structural element level (fair) and building level (unfair) [BmS, 2018]. Reuse on building level, where the load bearing structure as a whole is reused to give the building a new function (transformation) is not taken into account in the other researches and it is not within the scope of this research as well. Concluding reused and recycled contents are found in Equation F.3. All steel scrap returned to European steelmakers is recycled, but demand for new steel products exceeds the amount of scrap available. At present, about 50 per cent of the total EU steel production is derived from recycled steel scrap [Eurofer, 2018].

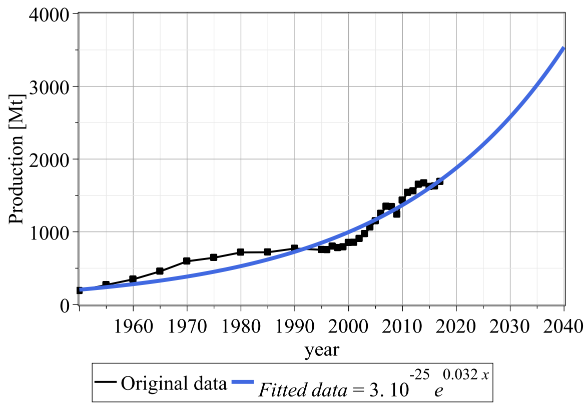


Figure F.1: Production of Crude Steel over the last 67 years, extrapolated for 25 years into the future.

As shown in Figure F.1 the increase in steel production rate can be formulated as Equation F.1. This relation shows that the world production of steel in 25 years will be 3022 Mt, instead of the 1689 Mt it is now. This ratio is the factor of which the reuse and recycle percentages have to be multiplied with, in order to get the realistic future reuse values. Note that a Reference Service Life (RSL) of 25 years is assumed. Use [Steelconstruction, 2016] for more steel reuse information.

$$Production\ rate_{steel} = 3 \cdot 10^{-25} \cdot e^{0.032x} \tag{F.1}$$

$$Y_s = \frac{Production_{now}}{Production_{future}} = \frac{1689}{3022} = 0.56 \tag{F.2}$$

Year	Author	Reused content (output)	Recycled content (output)	Landfill
2001	Steel Construction Institute (Heavy Sections)	13%	86%	1%
2001	Steel Construction Institute (Rebar)	1%	91%	8%
2006	Gorgolewski et al.	10%	90%	0%
2012	EUROFER (Heavy sections)	7%	91%	2%
	EUROFER (Rebar)	0%	98%	2%
2013	NFDC (Heavy sections)	7%	93%	0%
	NFDC (Rebar)	0%	98%	2%
2013	MRPI cert. BmS (Heavy sections)	49%	51%	0%
	Mean values	**9%**	**91%**	**1%**

Table F.1: Recycling and reuse percentages of steel in the UK and the Netherlands [Cullen and Drewniok, 2016; MRPI, 2013; steelconstruction.info, 2016]

$$R_1 = Y_s R_2 = 0.56 \cdot 0.91 \qquad = 0.51 \tag{F.3a}$$

$$R_2 = \frac{\text{mean value Recycled Content}}{100} = 0.91 \tag{F.3b}$$

$$R_3 = 0 \tag{F.3c}$$

$$R_4 = Y_s R_5 = 0.56 \cdot 0.08 \qquad = 0.04 \tag{F.3d}$$

$$R_5 = \frac{\text{mean value Reused Content}}{100} = 0.08 \tag{F.3e}$$

Technical Service Life

While structural steel has an infinitely long theoretical Technical Service Life (TSL), due to remelting scrap over and over, this is a non-realistic value to employ. The maximum service life of structural steel elements without recycling but including reuse is taken as 150 years. While this number is somewhat arbitrary, it is certain that steel elements can not be reused to infinity without some modifications to the material, so this is why a long, but non–infinite number is used.

$$TSL = 150 \ years$$

Loss of quality ratio

The ratio for any differences in quality between the secondary material and the primary material (down–cycling) are divided in a factor for reuse and recycle as stated in Equation F.4, where the quality of both the recycled and reused material is based on its economic value. Where recycling steel ables to get a secondary quality just as high as the primary material quality, this is not possible for reused steel elements in practise. Most of the time when structural steel elements (beams, columns etc.) are deconstructed and used in another building, the original and required element lengths are not the same. This means, beams have to be shortened and material losses are present. In order to take this given into account, an assumption for the Loss–of–Quality ratio of 0.8 is made.

$$\begin{aligned} K_{rec} &= \frac{Q_{S,recycled}}{Q_P} &&= 1 \\ K_{reu} &= \frac{Q_{S,reused}}{Q_P} &&= 0.8 \\ &\text{with:} \\ Q_P &= Q_{S,recycled} &&= 1 \\ Q_{S,reused} & &&= 0.8 \end{aligned} \tag{F.4}$$

F.1.2 Virgin material impact

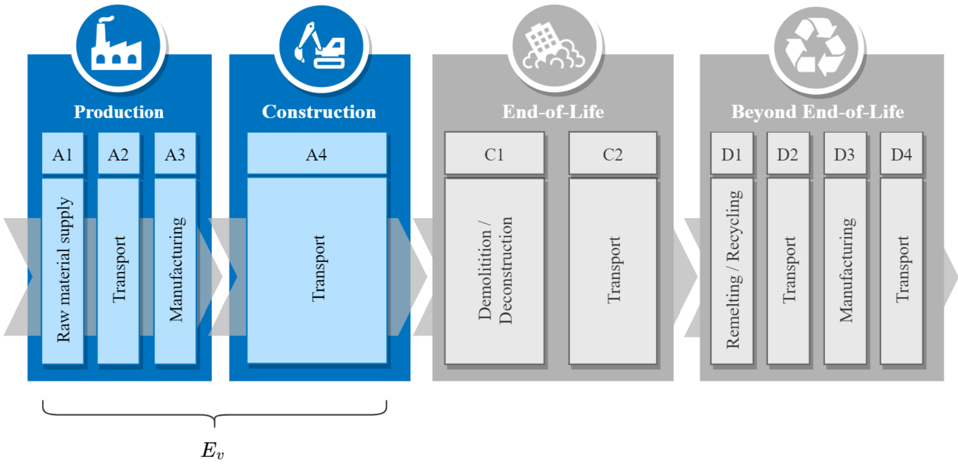


Figure F.2: To be considered LCA stages for E_v.

The virgin material impact is constructed of LCA phase A1–A4, as seen in Figure 4.2. The standard Nationale MilieuDatabase (NMD) values of "Steel, Heavy Construction Products" are taken. The standard NMD component 137 takes A1–A3 into account, transport to the construction site needs to be added to the total. A mean transport distance is taken from the research of van Maastrigt, which includes transport by ship from the BOF production plant in Tianjin, China, to the port of Rotterdam. Then, steel is transported to the 'mean site' by lorry to the middle of the Netherlands. This is summarized in Table F.2. The final normalized impact of virgin steel (A1–A4) is shown in Equation F.5, which sums up production and transport.

Module	Mode of transport	Origin	Destination	Distance
A4	Transoceanic freight ship	Tianjin, CN	Rotterdam, NL	23600 km
A4	Lorry	Rotterdam, NL	Emmeloord, NL	150 km
A4	Lorry	Emmeloord, NL	Zaltbommel, NL	130 km

Table F.2: Transport distances of steel heavy structural elements, according to [Maastrigt, 2019, p.143]

$$\begin{aligned} E_v &= A_1 + A_2 + A_3 && + A_4 \\ &= E_{virgin,production} && + \sum E_{Transport} \\ &= NMD_{Heavy\ construction\ steel,production} && + \sum NMD_{Transport} \end{aligned} \tag{F.5}$$

F.1.3 Recycle impact

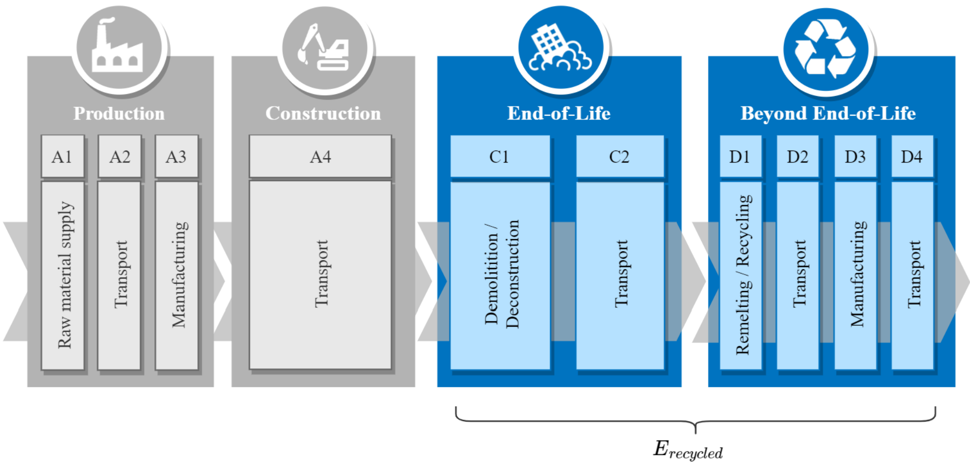


Figure F.3: To be considered LCA stages for $E_{recycled}$ and $E_{recycling,EoL}$.

There is a big difference in impact regarding the production of virgin steel (Integrated mill) or recycled steel from scrap metal (Electric Arc Furnace mill). The environmental impact according to the Environmental Product Declaration (EPD) of steel from the NMD of the production stage is taken as the impact of virgin steel. One tonne of steel produced from primary ore (through Basic Oxygen Furnace (BOF) route) uses two and a half times more energy than one tonne of steel produced from melting scrap (through Electric Arc Furnace (EAF) route) (EAF scrap 9.1–12.5 GJ/tcs and BOF virgin 19.8–31.2 GJ/tcs) [Yellishetty et al., 2011]. In addition, Burchart-Korol noted that the difference in environmental impact between EAF and BOF route is roughly 1:5.5 [Burchart-Korol, 2013]. This value is also found by Van Maastrigt in [Maastrigt, 2019].

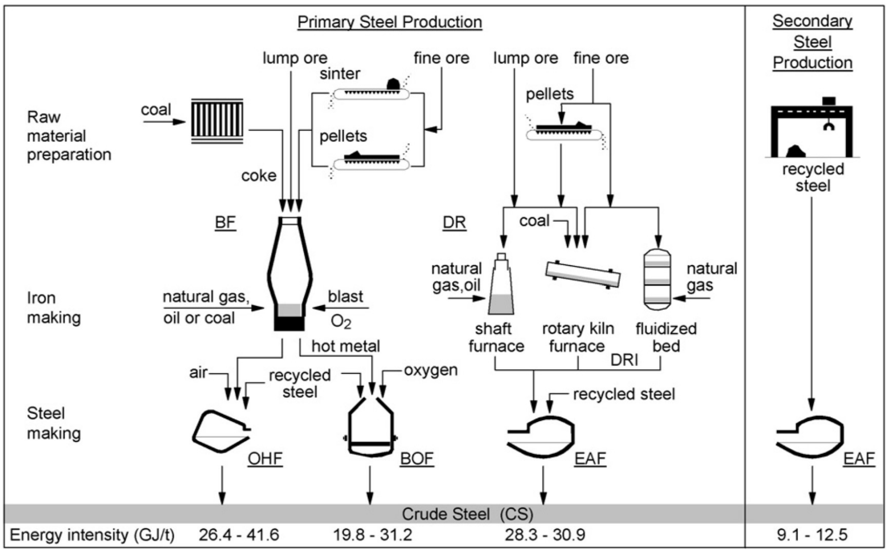


Figure F.4: Comparison of energy use for virgin vs. recycled steel through BOF and EAF route respectively [Yellishetty et al., 2011; Worldsteel, 2010]

ASSUMPTIONS: The lower bound factors of Figure F.4 in used energy between the different steel production methods are calculated in Equation F.6a. The method results of the research of Burchart-Korol are shown in Equation F.6b. The average of these two researches is taken as the final value of p_s. Notice that in the research of Yellishetty only energy use is taken into account, while Burchart-Korol calculates the environmental impact per impact category following the Product Category Rules. This means the factor in energy use is used in a broader sense as the factor in environmental impact, which is a simplified model of reality.

Moreover, it is assumed that the environmental impact of $E_{recycling,EoL}$ and $E_{recycled}$ are similar, due to the same processes being used.

Transport distances of of recycling are somewhat difficult to include. Of all Dutch steel scrap, 70% is exported abroad (mostly outside the EU), while 30% is recycled in the Netherlands [Teurlings, 2019]. The only EAF recycling plant in the Netherlands is Thyssen-Nedstaal in Alblasserdam. Of the remaining 70%, most steel is exported to China for recycling. In order to include these mean transport distances in a relatively easy manner, the Dutch transport part is neglected and the total transport of the recycling process is taken as 70% of the transport distance to China. This is shown in Table F.4.

$$p_{s,Yellishetty} = \frac{9.1}{19.8} = 0.46 \tag{F.6a}$$

$$p_{s,Burchart} = \frac{1}{5.5} = 0.18 \tag{F.6b}$$

$$E_{recycled,construction} = p_s \cdot E_{virgin,production} = 0.32 \cdot E_{virgin,production} \tag{F.7}$$

Module	Mode of transport	Origin	Destination	Distance	Averaged distance
C2, D2	Transoceanic freight ship	Rotterdam, NL	Tianjin, CN	23600 km	$0.7 \cdot 23600 = 16520$ km

Table F.4: Recycling transport distances of steel heavy structural elements, according to [Teurlings, 2019]

$$\begin{aligned} E_{recycled} &= C1 + C2 + D1 + D2 + D3 + D4 \\ &\text{with:} \\ C2 + D2 &= \sum NMD_{transoceanic\ ship} \\ D1 + D3 &= p_s(A_1 + A_2 + A_3) \end{aligned} \tag{F.8}$$

F.1.4 Reuse impact

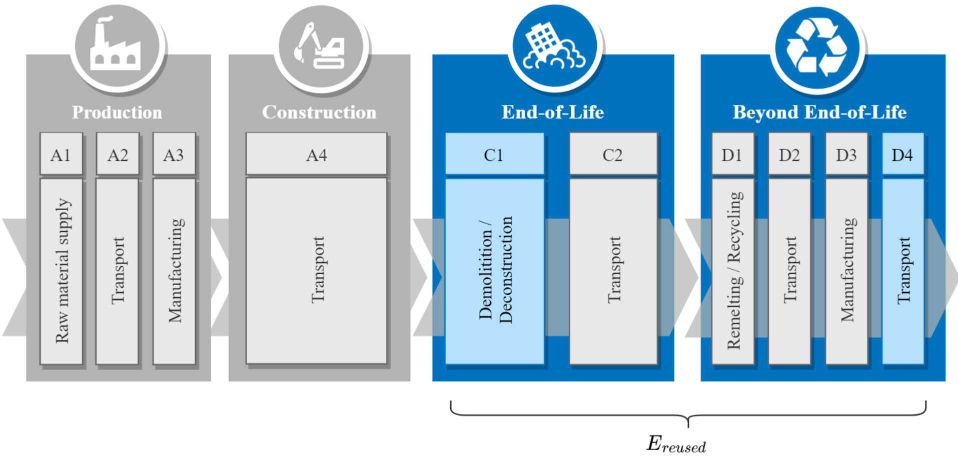


Figure F.5: To be considered LCA stages for E_{reused} and $E_{reusing,EoL}$.

The environmental impact of reusing a steel structure is researched by Maastrigt in [Maastrigt, 2019]. The impact of the deconstruction of steel (C1) is shown in Table F.5. In addition to the deconstruction process, the reuse impact is mostly dependent on the process of the distance between the original and new site. Transport distances for reuse are assumed fairly low with 50 km by lorry (D4), due to the fact that only abandoned buildings that are relatively close to the new project site are used as a donor structural framework. This distance is chosen arbitrary and not taken from the default CUR transport distances, as Silvius showed these values are not representative at all and sometimes can not even be seen as a upper limit in [Silvius, 2016]. Construction on the new site is not taken into account as construction at current site (A5) is not taken into account as well, due to this impact being insignificantly low with respect to the others according to Silvius.

Environmental Impact Category	Equivalent Unit	per kg steel
Abiotic Depletion fuels (ADPe)	Sb	0.00011167
Abiotic Depletion non–fuels (ADPf)	Sb	0
Global Warming Potential (GWP)	CO_2	0.03398
Ozone Layer Depletion (ODP)	CFC−11	0
Photochemical Oxidation (POCP)	C_2H_4	0.00003084
Acidification (AP)	SO_2	0.00008753
Eutrophication (EP)	PO_4	0.00002172
Human Toxicity (HTP)	1.4−DB	0.0003102
Freshwater Aquatic Ecotox. (FAETP)	1.4−DB	0.00002500
Marine Aquatic Ecotox. (MAETP)	1.4−DB	0.6941
Terrestrial Ecotoxicity (TETP)	1.4−DB	0.00001272

Table F.5: Used average environmental impact factors per kg steel extracted from an obsolete building from [Maastrigt, 2019, p.133] (LCA stage C1)

$$E_{reused} = C_1 + D_4 \tag{F.9}$$

When Design for Deconstruction is considered at the input or output phase, extra parameters are needed. Equation 4.11 shows the extra parameters P_{r4}, P_{r5} and BCI. Where the last parameter is explained in subsection 4.2.3, the first two still have to be determined. An average percentage of a load–bearing structure that is constructed out of reused elements at input side (P_{r4}) is taken. This percentage is derived from multiple IMd project where elements were reused in a new building. In the future, probably a bigger percentage of elements will be reused, due to the existence of Madaster (an online material passport database) and other incentives. The world is changing from a linear to a circular way of thinking, and a higher percentage of reuse is a part of this process.

$$P_{r4} = 0.75 \tag{F.10a}$$
$$P_{r5} = 0.75 \tag{F.10b}$$

Building Circularity Index

The Building Circularity Index (BCI) is elaborated in subsection 4.2.3. The Material Index (MI) is calculated at 0.93 and the Releasability Index (RI) is set at 0.6 and 0.1 for pinned and welded joints respectively. For the calculation behind these values see subsection 4.2.3 and C. A resulting BCI of 0.56 is achieved for a steel structure with pinned joints. When the Design for Deconstruction concept is applied (bolted connections), a BCI of 0.75 is achieved, a significant difference.

Parameters	
Material	Steel
CT	Pinned connection
CA	Accessible extra actions repairable damage
RSL	50 years
TSL	150 years
n=TSL/RSL	3
%virgin	44.56 %
%reuse	4.48 %
%recycle	50.96 %
%loss	0 %

Material Index (MI)	
MI	0.93
Releasability Index (RI)	
RI	0.6
Building Circularity Index (BCI)	
BCI	0.56

(a) Standard steel building.

Parameters	
Material	Steel
CT	Bolted connection
CA	Accessible extra actions without damage
RSL	50 years
TSL	150 years
n=TSL/RSL	3
%virgin	44.56 %
%reuse	4.48 %
%recycle	50.96 %
%loss	0 %

Material Index (MI)	
MI	0.93
Releasability Index (RI)	
RI	0.8
Building Circularity Index (BCI)	
BCI	0.75

(b) Steel building where the Design for Deconstruction concept is applied.

Figure F.6: Building Circularity Index for a steel framework.

F.1.5 Disposal impact

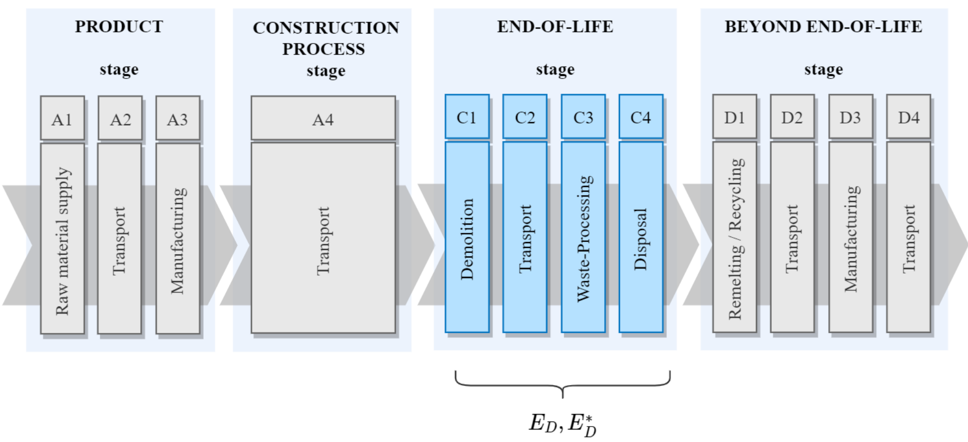


Figure F.7: To be considered LCA stages for E_D.

While in reality, disposal is a significant part of the total environmental impact, this is not the case with structural steel. With only 1% of the steel structures being disposed, this impact is negligible. The remaining 99% is considered in the reuse or recycle impact.

F.2 ENVIRONMENTAL IMPACT PARAMETERS OF CONCRETE

In this section the environmental impact per life cycle phase for both in–situ and hollow–core slabs are elaborated. The structure of the section is comparable to the steel parameter section, section F.1. Most parameters are used for both in–situ cast concrete and hollow–core slabs. If not, a proper distinction is made in the corresponding subsections.

F.2.1 General material–related parameters

The signed concrete agreement by various large parties in the Dutch concrete sector has meant a major step towards making concrete more sustainable. The aim is to reuse all concrete from demolished buildings and other concrete structures from 2030 onwards. This means that 15 to 20% of the Dutch need for concrete can be covered. Higher rates are not possible, due to much more being built than demolished [BetonInfra, 2016].

For the coming years, it is expected that suitable concrete granulate released from demolition can replace a maximum of 30% of the use of primary gravel. In addition, the benefit in terms of environmental impact is very limited. The concrete granulate must be processed as close as possible to the production location [Hofstra et al., 2006]. Transport over longer distances would have a negative impact on the environmental impact compared to primary gravel and would probably lead to a worse result on the CO_2 emission component. A higher recycled content is not possible without altering the structural properties of the concrete.

Currently the largest part of End–of–Life (EoL) concrete is being recycled in low value applications such as fill or road sub grade as it presents excellent compaction properties [Nusselder et al., 2015]. In 2009 only 1.9% of all concrete was processed to become recycled aggregate [Inspectie Leefomgeving en Transport., 2013].

Author	Recycled content (input)	Recycling rate (output) [non–structural]	Landfill
[Chini, 2005]	-	80%	20%
[Marinković et al., 2013]	1%	80%	20%
[Schut et al., 2015]	4%	95%	-
[BetonInfra, 2016]	20% (theoretical)	-	-
Mean values	**2%**	**80%**	**20%**

Table F.6: Recycling percentages of concrete aggregate in the Netherlands, where recycling rate (output) is taken as recycling into road foundation (down-cycling).

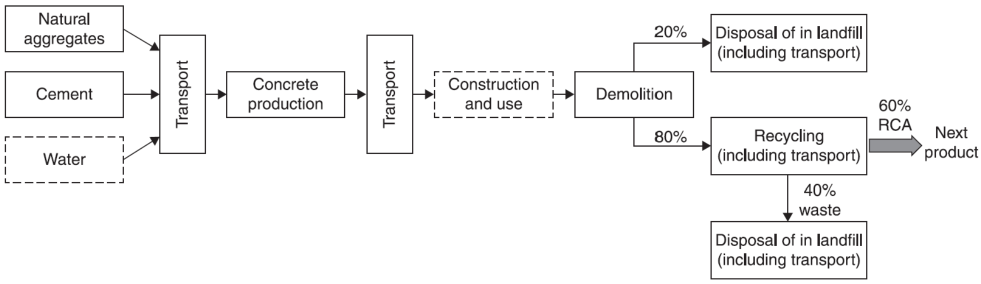


Figure F.8: Concrete life cycle and its recycling rates according to [Marinković et al., 2013].

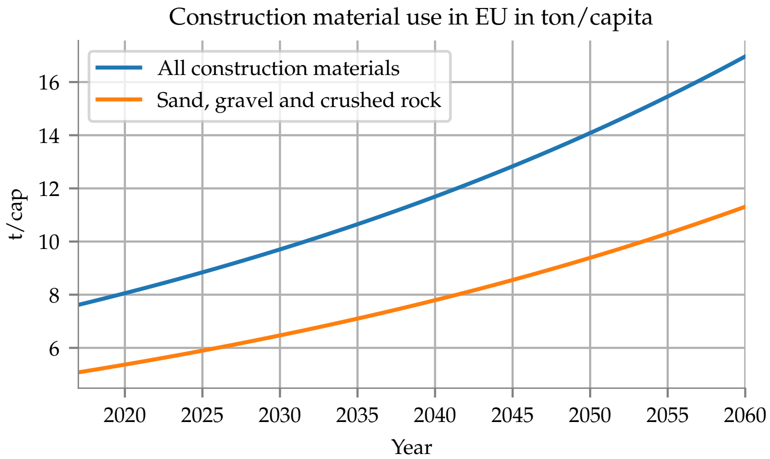


Figure F.9: Future construction materials use and the share of concrete production by [OECD, 2019, p.134].

Figure F.9 indicates a significant increase of concrete production, which can mean a decrease of recycled content in future concrete, due to its demand being much higher than its supply. However, the use of recycled content in concrete production is still at an early stage with only 2% of concrete being recycled for new concrete. In the near future, landfill is expected to become more expensive due to land shortage, which will foster the use of Recycled Concrete Aggregate (RCA) [Dodoo et al., 2009]. This motion is expected to (partially) counteract the increase in concrete production. For this reason the production ratio is not taken into account for concrete.

$$R_1 = \frac{\text{mean value Recycled Content}}{100} = 0.02 \tag{F.11a}$$

$$R_2 = \frac{\text{mean value Recycling Rate}}{100} = 0.8 \tag{F.11b}$$

$$R_3 = 0 \tag{F.11c}$$

$$R_4 = \frac{\text{mean value Reused Content}}{100} = 0 \tag{F.11d}$$

$$R_5 = R_4 = 0 \tag{F.11e}$$

Technical Service Life

There are tow main factors which decide the Technical Service Life of a concrete structure, the concrete mixture and the buildings environmental class. In this research, an average mixture of C30/37 and class of XC1 is assumed. Multiple design guidelines and equations in order to calculate the estimated service life of a concrete structure are existent, such as the methods described in [Selvaraj, 2016] and [Van Der Wegen et al., 2012]. However, these methods need specific input on corrosion rate, splash zones, rebar diameter and more. Due to this tool being used in the conceptual design phase, these parameters are not yet known and thus have to be estimated. The assumption is made that the load bearing structure is mostly (but not totally) closed off from environmental influences such as moist and carbonation by the façade, which results in a durability class. For this reason, a relatively long Technical Service Life of 150 years is applied for both in-situ concrete and the hollow–core slabs.

Class	Environmental description	Example
XC1	Dry or permanently wet	Concrete inside buildings with low humidity Concrete remains under water

Table F.7: Eurocode table of environmental classes withing corrosion initiated by carbonation [NEN, 2011a].

$$TSL = 150\ years$$

Loss of quality ratio

The loss of quality ratio for concrete is taken as the economical ratio corresponding to the primary and secondary product, respectively the C30/37 concrete and the the Recycled Concrete Aggregate, known as concrete rubble. On average, the price of a m^3 of C30/37 quality concrete is €140,- [Betonmortel.net, 2019], while a tonne of rubble costs €20,- [Janssen Group, 2019; Zandcompleet, 2019; GrindWereld.nl, 2019].

Although LCA rules state that you should not use an economic relationship unless it really cannot be otherwise, this is the only solution here. It should be mentioned here that the rubber prices fluctuate violently, and because of what is stated on the previous page implying that the prices will rise in the future, this calculation is not taken into account.

$$\begin{aligned} C30/37 &= 140\ €/m^3 = 140 \cdot 2.4€/m^3 \cdot tonne/m^3 && = €\ 336/t \\ \text{RCA (rubble)} & && = €\ 20/t \end{aligned}$$

The quality ratio of secondary reused elements of concrete is kept the same as the quality of secondary steel, where, for example, a concrete floor could be cut and used as a wall somewhere else. The value is implicitly not reduced by this, but due to the less effective surface area (you do not use the entire floor) a factor of 0.8 has been taken into consideration.

$$\begin{aligned} K_{rec} &= \frac{Q_{S,recycled}}{Q_P} = \frac{20}{336} && = 0.06 \\ K_{reu} &= \frac{Q_{S,reused}}{Q_P} && = 0.8 \end{aligned} \tag{F.12}$$

F.2.2 Virgin material impact

The virgin material impact is constructed of LCA dphase A1-–A4, as seen in Figure F.2. NMD and MRPI values for Phase A1–A3 are taken, but transport to the construction sit (A4) is specified separately.

Hollow–core slab

Due to the hollow-core slabs having a totally different production process compared to ordinary in–situ cast concrete, the standard MRPI values of "VBI PV 200 Groen" [VBI, 2013] are taken as reference for LCA phase A1–A3. Transport to the construction site needs to be added to the total. The environmental impact of other hollow–core slabs is scaled up based on their weight ratio. With 5 locations of production in the Netherlands, divided from north to south, but mostly on the east side of the Netherlands, the mean transport distances of the production plant to the construction site are relatively small with 80 km one–way [VBI, 2019a]. An average load percentage of 65% per ride is used.

Cast in–situ concrete
Despite the environmental class of XC1 used as a reference point, the standard NMD value of "145 — Civil construction C30/37 XD3, XF2 S3 0% granulate" is used for production phase A1–A3. If looking at the environmental impact of the different environmental classes, the difference between XC1 and XD3 is not big. With aforementioned NMD value being a verified value proposed by Stichting Bouwkwaliteit (SBK), this value is assumed. Furthermore, Ontwerptool Groen beton [Betonhuis, 2019] showes that concrete with a higher percentage of recycled granulate has a higher environmental impact than mixtures with a lower percentage of granulate. This paradoxical effect is due to the recycled granulate which absorbs a lot of water in the mixture, which results in the addition of water, which results in the addition extra cement to the mixture in order to comply with the required water/cement ratio. In this way, the environmental benefit of using recycled granulate is (more than) eliminated by the addition of cement. For this reason, not the standard 20% granulate mixture but the 0% granulate mixture is assumed.

With concrete plants spread all over the Netherlands, the distance from production to construction site is as small as the hollow–core slab transport distance of 80 km one–way. For this transport, the NMD's "T0016 — Concrete Truckmixer NL - average" is used.

Reinforcement
With reinforcement mostly being produced in the Netherlands, but only on a few locations, a mean transport distance to construction site of 120 km is used.

F.2.3 Recycle impact

The impact of recycling can be seen as the sum of LCA stage C1–D4, which is visualized in subsection F.1.3, Figure F.3. However, the recycling process of concrete is a little different than the one from steel. The recycling of concrete happens on site with a Jaw Crusher, Impact Crusher and Mechanical Grinder, see Figure F.11. Moreover, the forthcoming aggregate is ready to use immediately. This means transport stage C2 and D2 and Manufacturing stage D3 are eliminated from the recycling process, which results in the remaining stages of Figure F.10.

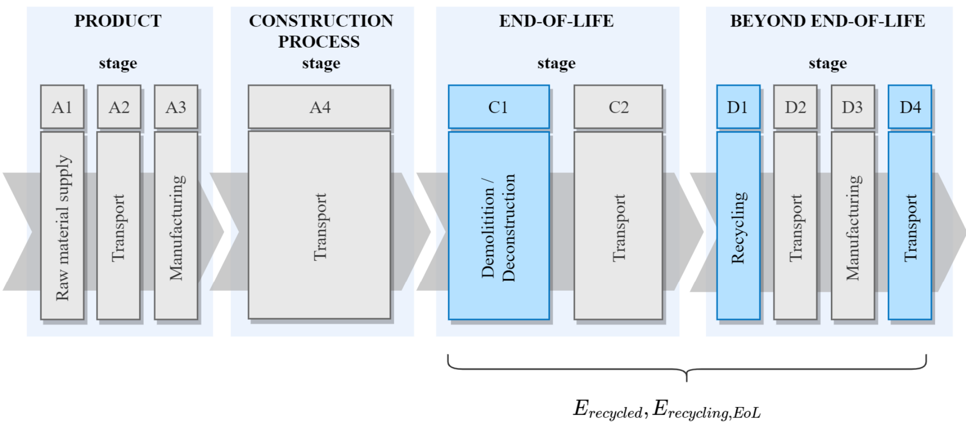


Figure F.10: To be considered LCA stages for $E_{recycled}$ and $E_{recycling,EoL}$.

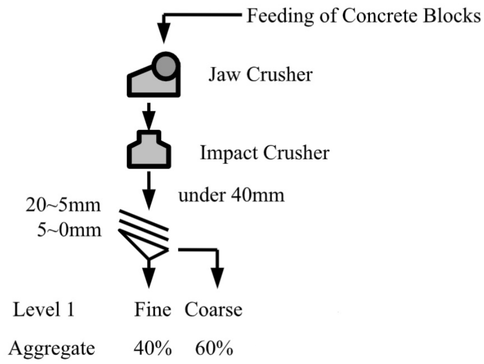


Figure F.11: Flow of the recycling process for level 1 recycled aggregate.

As can be seen in Figure F.10, demolition, recycling and transport to site has to be taken into account for the recycling impact. For the demolition of concrete, NMD value "E0073 — Demolition concrete (tescop) (NL)" is chosen.
The recycling of concrete is done on site using a jaw crusher and impact crusher, in order to acquire level 1 concrete aggregate, as shown in Figure F.11. The environmental profile of "Concrete granulate 4/x [BRBS], 2013, PRODUCTIE c2" is taken as an assumption for this process.
Lastly, the transport from one to the other site has to be considered. Same transport distances as the reuse distances for steel are used (50 km), since this is also performed on site.

Reinforcement
The recycling of the reinforcement in both the hollow–core slabs as in–situ cast concrete is assumed as the summed impact of recycling concrete (crushing) and recycling steel (remelting). Regarding transport distances LCA stage C2, D2 and D4 are included, where the recycling plant (remelting) in IJmuiden is considered. This results in a total transport distance of:

$$C2 + D2 + D4 = 150 + 100 + 100 = 350\ km \tag{F.13}$$

F.2.4 Reuse impact

In the standard scenario, Scenario 1 mean—mean, reuse of concrete ($R4$ and $R5$) is not taken into account. However, in the advanced scenarios which include Design for Deconstruction (DfD) at in- or output, this can be taken into account. Not much is known about the environmental impact of reusing concrete, due to the fact that it is not being done yet. Looking at the considered LCA stages of Figure F.5, deconstruction and transport to site is considered. Maastrigt noted in [Maastrigt, 2019] that time–wise, the deconstruction of a building is approximately double as effective as construction of a building. While this research was focused on the erection and deconstruction of steel structures, this conclusion is extended to the deconstruction of concrete due to the fact that no actual data on the deconstruction of concrete structures is available. The transport distances for reusing concrete from old to new site are assumed the same as for steel, 50 km.

$$E_{deconstruction} = \frac{1}{2} MRPI_{Construction\ VBI\ hollow\ slab\ floor} \tag{F.14}$$

Percentage of reused elements at in- and output
Reusing old concrete elements in the new building (reuse at input) is hardly used to date, due to excessive costs. However, there still is the option to apply reused concrete elements at input. However, the percentage of elements being reused is significantly lower than with the use of steel because it is so hard to apply. An

arbitrary value of $P_{r4} = 0.2$ is applied. Chances are a higher percentage of the structural elements can be reused in the future, but this is not taken into account. Therefore $P_{r4} = P_{r5} = 0.2$.

Building Circularity Index
The BCI of concrete is totally different than steel, mostly due to the wet connections. These connections are set–up in Figure F.12 as welded connections. The result is a low $BCI = 0.21$. Which implies that concrete is an unfavorable material to apply the design for deconstruction concept to. When the Design for Deconstruction concept is actually applied, the BCI changes to $BCI = 0.58$.

Parameters	
Material	Concrete
CT	Welded Connection
CA	Accessible extra actions irreparable damage
RSL	50 years
TSL	150 years
n=TSL/RSL	3
%virgin	98 %
%reuse	0 %
%recycle	2 %
%loss	20 %

Material Index (MI)	
MI	0.82
Releasability Index (RI)	
RI	0.25
Building Circularity Index (BCI)	
BCI	0.21

(a) Standard concrete building.

Parameters	
Material	Concrete
CT	Bolted connection
CA	Accessible extra actions repairable damage
RSL	50 years
TSL	150 years
n=TSL/RSL	3
%virgin	98 %
%reuse	0 %
%recycle	2 %
%loss	20 %

Material Index (MI)	
MI	0.82
Releasability Index (RI)	
RI	0.7
Building Circularity Index (BCI)	
BCI	0.58

(b) Concrete building where the Design for Deconstruction concept is applied.

Figure F.12: Building Circularity Index for a concrete framework.

F.2.5 Disposal impact

As visualized in Figure F.7, the disposal of concrete can be separated in LCA stage C1–C4, demolition, transport, waste–processing and disposal respectively. For the demolition and disposal the NMD/Ecoinvent values of "E0073 — Demolition concrete (tescop) (NL)" and "WPNL0003 — 0240-sto&Stort beton, cellenbeton (treatment of waste concrete, inert material landfill — Cut-off, U)" are taken respectively. Due to these values being "Cat 3 data", which means unverified, an additional environmental burden of 30% needs to be added to it. Regarding transport from the building site (which is the waste–processing plant due to on–site processing) to the disposal site is taken as 100 km by lorry.

F.3 ENVIRONMENTAL IMPACT PARAMETERS OF TIMBER

In this section the environmental impact per life cycle phase for the timber elements are elaborated.

F.3.1 General material–related parameters

Timber structures are generally not reused and mostly not even recycled. Nibes waste scenario for sawn timber show a small portion of the waste being recycled or reused, while glulam is not recycled or reused at all (Table F.8).

Material	Sawn timber	Glulam
Nibe scenario	WNL0110 — wood 'clean', beams, planks	WNL0017 — wood, contaminated (i.a. painted, preserved)
Region	Netherlands	Netherlands
To be left (%)	0	0
Landfill (%)	5	5
Incineration (%)	80	95
Recycling (%)	10	0
Reuse (%)	5	0

Table F.8: Assumed waste scenarios for sawn timber and glulam respectively. Taken from Nibes environmental impact database [NIBE, 2019].

The research of Hildebrandt et al. states the average annual growth of sawn timber at – 0.80% during 2000 — 2014, while the average annual growth of glulam is stated at 8.57% during that same period [Hildebrandt et al., 2017]. Extrapolating these numbers result in the expected growth, visualized in Figure F.13. In order to acquire the production rates, the difference in production between 2020 and 2045 is used, which corresponds to a RSL = 25 years.

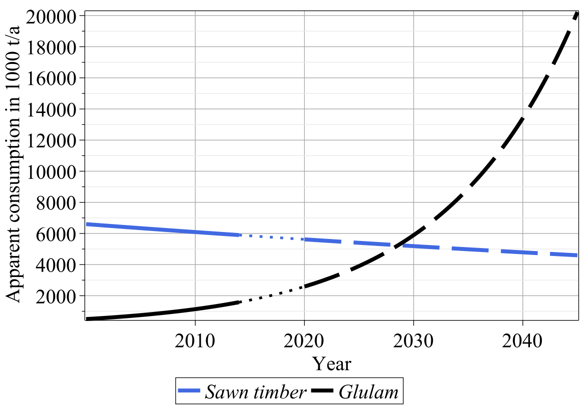


Figure F.13: Production sawn timber and glued laminated timber, measured over the period 2000 — 2014, extrapolated over 2014 — 2045. [Hildebrandt et al., 2017].

$$Y_{sawn} = \frac{\text{Production sawn timber}_{now}}{\text{Production sawn timber}_{future}} = \frac{5621}{4598} = 1.22 \tag{F.15a}$$

$$Y_{glulam} = \frac{\text{Production glulam}_{now}}{\text{Production glulam}_{future}} = \frac{2598}{20226} = 0.13 \tag{F.15b}$$

$$R_{1,sawn} = Y_{sawn} \cdot R_{2,sawn} = 1.22 \cdot 0.10 = 0.12 \tag{F.16a}$$

$$R_{2,sawn} = \frac{\text{Recycled Content Sawn Timber}}{100} = 0.10 \tag{F.16b}$$

$$R_{3,sawn} = \frac{\text{Incineration rate Sawn Timber}}{100} = 0.80 \tag{F.16c}$$

$$R_{4,sawn} = Y_{sawn} \cdot R_{5,sawn} = 1.22 \cdot 0.05 = 0.06 \tag{F.16d}$$

$$R_{5,sawn} = \frac{\text{Reused Content Sawn Timber}}{100} = 0.05 \tag{F.16e}$$

$$R_{1,glulam} = R_{2,glulam} = R_{3,glulam} = R_{4,glulam} = 0 \tag{F.17a}$$

$$R_{3,glulam} = \frac{\text{Incineration rate Glulam}}{100} = 0.95 \tag{F.17b}$$

Technical Service Life

Following NEN-EN 335, a Use Class 2 is assumed for the timber structural system. This means "Situations in which the wood or wood-based product is under cover and not exposed to the weather (particularly rain and driven rain) but where occasional, but not persistent, wetting can occur. In this use class, condensation of water on the surface of wood and wood-based products may occur. Attack by disfiguring fungi and wood-destroying fungi is possible. Attack by wood-boring insects, including termites, is possible although the frequency and importance of the insect risk depends on the geographical region)." [NEN, 2013b]. This results in an according Risk Class 2 following NEN-EN 1995-1-1 [NEN, 2011b].

Along with the Risk Class, the durability class is the durability classification of wood species. There are five classes for the natural durability of the heartwood against fungi and the like. In this research, only coniferous wood is considered for both softwood as glued laminated timber, which usually belong in durability class 3. The relation between the corresponding risk and durability classes for a desired 25 year service life is elaborated in Table F.9. It can be concluded that natural durability is just sufficient, but a longer technical service life than 25 years is not deemable without preservation. A TSL of 75 years is assumed only with preservation measures applied.

Risk Class	Durability Class 1	2	3	4	5
1	O	O	O	O	O
2	O	O	**O**	(O)	(O)
3	O	O	(O)	(O) – (X)	(O) – (X)
4	O	(O)	(X)	X	X
5	O	X	(X)	X	X

Table F.9: Preservation recommendations based on a desired service life of 25 years [Stichting Probos, 2009]. Relation between risk and durability classes [NEN, 2018].

O: natural durability sufficient.
(O): natural durability is sufficient in principle, but under certain circumstances preservation is recommended.
(O) – (X): natural durability may be sufficient, but the choice of wood, the impregnability and the application determine the desirability of preservation.
(X): preservation recommended, but for certain applications the natural durability can be enough.
X: preservation required.

Loss of quality ratio

The loss of quality ratio of timber is taken as the economical ratio corresponding to the primary and secondary product, respectively sawn timber beams and wood chips. On average, the price of sawn timber beams is €505,- /m^3, while wood chips are sold at €25,- /m^3 [Bouwonline.com, 2019; De Houtboer, 2019; Brouwer boomschorshandel, 2019; Boomschors.net, 2019].

The research of Chini and Acquaye has shown that the mechanical properties of second-hand timber elements are generally similar or even better than virgin timber [Chini and Acquaye, 2001]. The value is implicitly not reduced by this. However, the same research has shown that reusable elements yield half as much as new wooden elements. Bids are typically this low due to the materials needed to be trimmed down to standard sizes and the volume was not large enough. The major reason for downgrading the timber was the presence of knots, end splits and primarily gouges that occurred during the deconstruction process. For this reason, a reduction factor of 0.5 has been taken into consideration, see Equation F.12

$$\begin{aligned} K_{rec} &= \frac{Q_{S,recycled}}{Q_P} = \frac{25}{505} &&= 0.05 \\ K_{reu} &= \frac{Q_{S,reused}}{Q_P} &&= 0.5 \end{aligned} \tag{F.18}$$

F.3.2 Virgin material impact

Material	NMD code	Description	Shadow price
Softwood	422	European softwood, dried (n=15%, 496 kg/m^3), planed, from sustainable managed forest [VVNH]	€ 0.03
Glulam	423	Laminated European softwood, dried (n=12%, 507 kg/m^3), from sustainable managed forest [NVL]	€ 0.07

Table F.10: Timber NMD environmental profiles used for the production stage (A1–A3). [NIBE, 2019]

Manufacturing of timber elements (beams, planks etcetera) is done in the Netherlands sawmill throughout the country. For this reason, a small transport distance (A4) of 80 km by truck is used.

F.3.3 Recycle impact

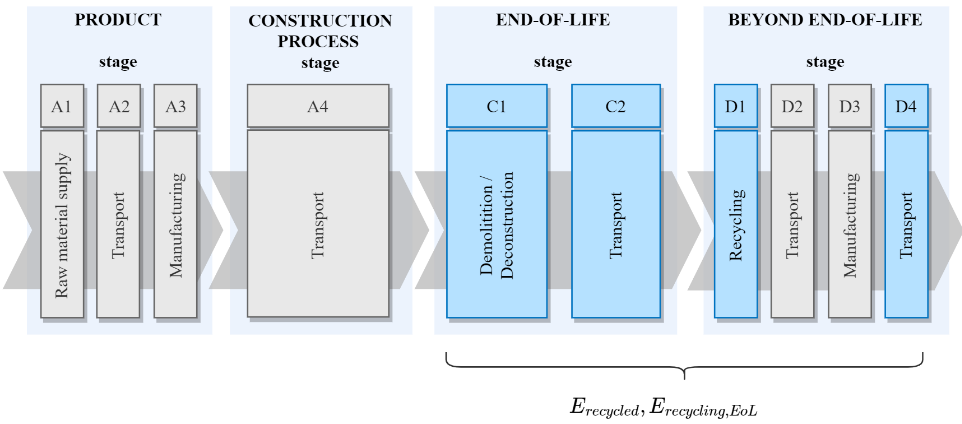


Figure F.14: To be considered LCA stages for $E_{recycled}$ and $E_{recycling,EoL}$.

Recycling impact for timber is taken as the sum of life cycle stages C1 — D4 (Figure F.10. The same demolition impact as steel elements is assumed, since the structural element sizes are similar and are deconstructed/demolished in a similar fashion. Only the weight per element differs when steel and timber elements are compared, but this is irrelevant for the environmental profile since these work per kilogram instead of per cubic meter. Transport distance for stage C2 are assumed similar to concrete, as both recycle plants are just as scattered throughout the Netherlands. The recycled timber replaces the virgin "Wood chips, dry, measured as dry mass (EU)" as stated in the NMD.

The reuse percentages for timber assumed are $P_{R4} = 0.5$ and $P_{R5} = 0.5$.

F.3.4 Reuse impact

Research showed that the dismantling ratio (or deconstruction) of wooden waste is approximately the same as non wooden waste such as concrete or steel [Nakajima and Futaki, 2002]. For this reason, and the similar nature of the connections as steel structures, the deconstruction impact of steel/kg is taken for timber as well.

Building Circularity Index
The BCI of timber is somewhat similar to steel, the result is a relatively low $BCI = 0.28$, see Figure F.15. However, when the Design for Deconstruction concept is applied here, the BCI changes to $BCI = 0.56$.

Parameters	
Material	Glulam
CT	Kitted connection
CA	Accessible extra actions repairable damage
RSL	50 years
TSL	75 years
n=TSL/RSL	1.5
%virgin	100 %
%reuse	0 %
%recycle	0 %
%loss	0 %
Material Index (MI)	
MI	0.70
Releasability Index (RI)	
RI	0.4
Building Circularity Index (BCI)	
BCI	0.28

(a) Standard timber building.

Parameters	
Material	Glulam
CT	Bolted connection
CA	Accessible extra actions without damage
RSL	50 years
TSL	75 years
n=TSL/RSL	1.5
%virgin	100 %
%reuse	0 %
%recycle	0 %
%loss	0 %
Material Index (MI)	
MI	0.70
Releasability Index (RI)	
RI	0.8
Building Circularity Index (BCI)	
BCI	0.56

(b) Timber building where the Design for Deconstruction concept is applied.

Figure F.15: Building Circularity Index for a timber framework.

F.3.5 Disposal impact

The disposal of timber is split up into demolition of the structure, transport to landfill and lastly the actual disposal. As mentioned before, the demolition of a timber structure is assumed similar to a steel structure. Distance to landfill is assumed 50 km. NMD value of "0245-sto&Stort hout, 'schoon' (o.b.v. Waste wood, untreated Europe without Switzerland— treatment of waste wood, untreated, sanitary landfill — Cut-off, U)" is assumed for disposal.

F.3.6 Incineration impact

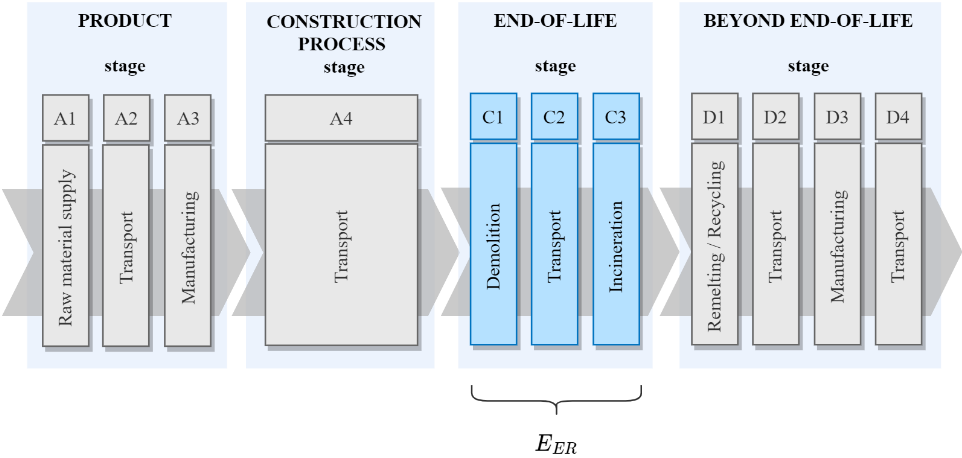
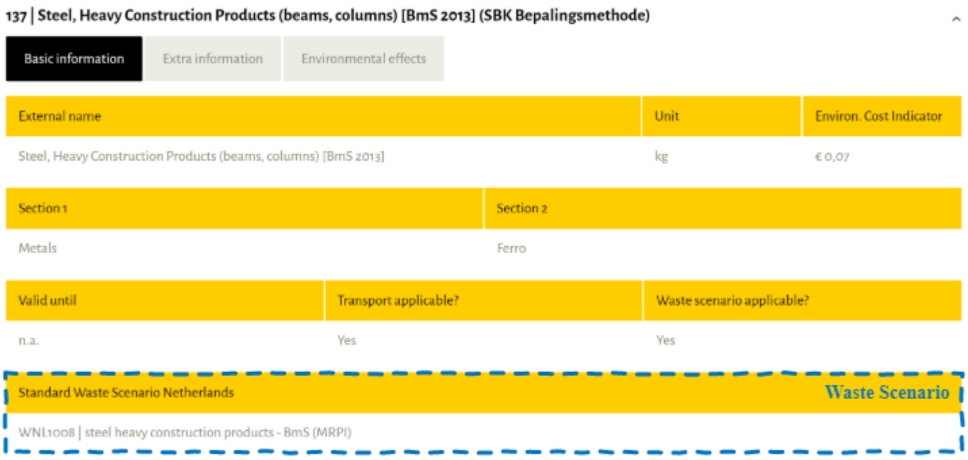


Figure F.16: To be considered LCA stages for the incineration phase E_{ER}.

Besides the standard impact categories of subsection F.3.1, F.3.2, F.3.3, F.3.4 and F.3.5, timber has an additional impact category regarding the incineration process. With 80% of timber beams and planks currently being incinerated, energy recovery can have a significant impact reduction. In the Netherlands, 91% Of all energy is produced through fossil resources and the remaining 9% by renewable resources [CBS, 2019]. In order to comply with these numbers, the original incineration part of the PEF equation (Equation 4.6) is adapted to Equation F.19. The total environmental impact due to the incineration is assumed as the sum of stage C1—C3, as visualized in Figure F.16.

$$
\begin{aligned}
E_{incineration} &= R_3(E_{ER} - LHV(R_r \cdot E_{SE,r} + R_f \cdot E_{SE,f})) \\
&\text{with:} \\
E_{ER} &= \text{Emissions due to the Energy Recovery process} \\
&\quad \text{[NMD: WPNL0026 — verbranden hout]} \\
E_{SE,r} &= \text{Avoided renewable energy production emissions} \\
&\quad \text{[NMD: E0081 — vermeden energieproductie} \\
&\quad \text{hernieuwbare grondstoffen]} \\
E_{SE,f} &= \text{Avoided fossil energy production emissions} \\
&\quad \text{[NMD: E0080 — vermeden energieproductie} \\
&\quad \text{fossiele grondstoffen]} \\
LHV &= \text{Lower Heating Value of timber [13.99 MJ/kg]} \\
&\quad \text{[NMD: WPNL0026 — verbranden hout]} \\
R_3 &= \text{Percentage of timber which is being incinerated at the} \\
&\quad \text{end–of–life phase} \\
R_r &= \text{Percentage of the total energy produced in the} \\
&\quad \text{Netherlands coming from renewable resources} \\
R_f &= \text{Percentage of the total energy produced in the} \\
&\quad \text{Netherlands coming from fossil resources}
\end{aligned}
\tag{F.19}
$$

G | INPUT PARAMETER TABLES



137 | Steel, Heavy Construction Products (beams, columns) [BmS 2013] (SBK Bepalingsmethode)

Basic information | Extra information | Environmental effects

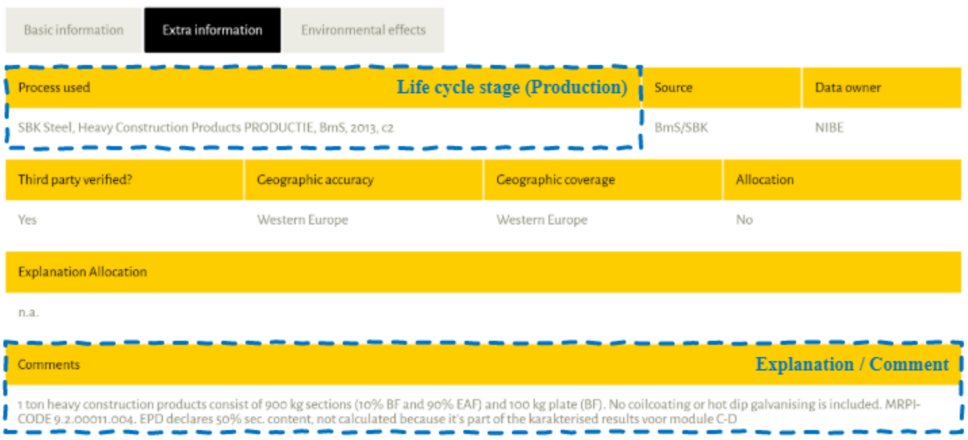
External name	Unit	Environ. Cost Indicator
Steel, Heavy Construction Products (beams, columns) [BmS 2013]	kg	€ 0,07

Section 1	Section 2
Metals	Ferro

Valid until	Transport applicable?	Waste scenario applicable?
n.a.	Yes	Yes

Standard Waste Scenario Netherlands
WNL1008 | steel heavy construction products - BmS (MRPI)

(a) Basic information



Basic information | Extra information | Environmental effects

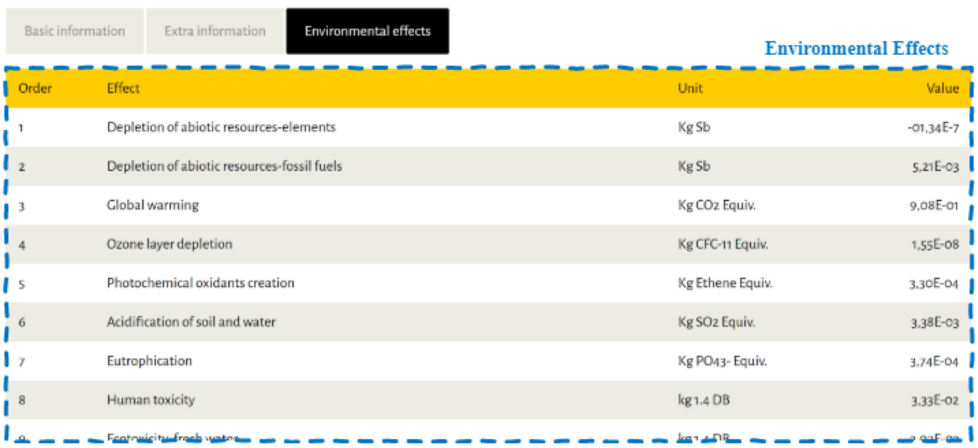
Process used	Source	Data owner
SBK Steel, Heavy Construction Products PRODUCTIE, BmS, 2013, c2	BmS/SBK	NIBE

Third party verified?	Geographic accuracy	Geographic coverage	Allocation
Yes	Western Europe	Western Europe	No

Explanation Allocation
n.a.

Comments
1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D

(b) Exra information



Basic information | Extra information | Environmental effects

Order	Effect	Unit	Value
1	Depletion of abiotic resources-elements	Kg Sb	-01,34E-7
2	Depletion of abiotic resources-fossil fuels	Kg Sb	5,21E-03
3	Global warming	Kg CO2 Equiv.	9,08E-01
4	Ozone layer depletion	Kg CFC-11 Equiv.	1,55E-08
5	Photochemical oxidants creation	Kg Ethene Equiv.	3,30E-04
6	Acidification of soil and water	Kg SO2 Equiv.	3,38E-03
7	Eutrophication	Kg PO43- Equiv.	3,74E-04
8	Human toxicity	kg 1.4 DB	3,33E-02
[illegible]	[illegible]	[illegible]	[illegible]

(c) Environmental effects

Figure G.1: Example of the NIBE EPD application, environmental profiles database. Here, the environmental profile of heavy construction steel is shown.

LCA Database

Totaalprofiel constructiemateriaal — Production (A1, A2, A3)

Materiaal	nr.	Materiaalcode en omschrijving	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
S235	137	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	-1.34E-07	5.21E-03	9.08E-01	1.55E-08	3.30E-04	3.38E-03	3.74E-04	3.33E-02	3.02E-03	6.34E+00	4.68E-04	€ 0.0669	c2	€ 0.0669	Production (A1-A3)	1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D
C30/37	146	Civil construction C30/37 XD3, XF2 S3 0% granulate	1.18E-07	2.29E-04	5.96E-02	2.68E-09	2.43E-05	2.59E-04	3.58E-05	9.66E-03	2.25E-04	2.10E+00	9.25E-05	€ 0.0055	c2	€ 0.0055	Production (A1-A3)	
Rebar	257	Steel, Reinforcement [VWN]	2.16E-07	7.61E-03	1.37E+00	9.36E-09	4.72E-04	1.89E-03	3.30E-04	2.72E-02	1.28E-03	3.95E+00	1.82E-03	€ 0.0833	c2	€ 0.0833	Production (A1-A3)	
KPV		Kanaalplaatvloer 200 [MRPI]	4.20E-05	1.10E-01	2.40E+01	1.10E-06	1.00E-02	9.10E-02	1.50E-02	6.00E+00	1.20E-01	8.20E+02	1.20E-01	€ 2.35	c2	€ 2.3500	Production (A1-A3)	per m2 ipv per kg
Softwood	422	European softwood, dried (n=15%, 496kg/m3), planed, from sustainable managed forest [VVNH]	5.69E-07	1.80E-03	2.56E-01	3.16E-08	1.87E-04	1.47E-03	3.09E-04	1.08E-01	3.33E-03	1.46E+01	2.06E-03	€ 0.03	c2	€ 0.0332	Production (A1-A3)	Europees Naaldhout, duurzaam bos, gezaagd, gedroogd, ongeschaafd bij houthandel, Centrum Hout, PRODUCTIE (A1-A3). Europees Naaldhout (vuren, grenen lariks, douglas en dennen) 496 kg/m3, uit Noord Eruopa (Zweden, Finland, Duitsland. Rusland en overige landen), gedroogd (15%) en geschaafd af Nederlandse houthandel. Het profiel is omgerekend van m3 naar kg door het te delen door zijn soortelijk gewicht
Glulam	423	Laminated European softwood, dried (n=12%, 507kg/m3), from sustainable managed forest [NVL]	1.28E-06	4.43E-03	5.81E-01	6.72E-08	7.75E-04	2.71E-03	6.28E-04	2.68E-01	1.16E-02	3.51E+01	3.61E-03	€ 0.07	c2	€ 0.0745	Production (A1-A3)	Te gebruiken voor afmetingen binnen de volgende range: hoogte 10x240 cm, breedte 6x24 cm, lengte 50 m maximaal.Technische informatie product: vooral vuren gemiddelde volumieke massa 507 kg/m³ bij 12% vochtgehalte; lijmaandeel PUR, MUF, PRF respectievelijk 0,03, 1,94, 0,09%; verschillende sterkteklasse: GL24h, GL28c, GL32c (NEN-EN 14080); levensduur feitelijk oneindig; brandklasse D. Het profiel is omgerekend van m3 naar kg door het te delen door zijn soortelijk gewicht
Glulam_V_star	489	Wood chips, dry, measured as dry mass (EU)	1.40E-07	4.32E-04	5.85E-02	7.25E-09	6.17E-05	3.25E-04	6.68E-05	2.12E-02	6.77E-04	1.64E+00	2.06E-04	€ 0.01	C3	€ 0.0091	Production (A1-A3)	
C30/37_V_star	60	Mixed granulate (road construction) 0/31.5 [BRBS]	3.30E-10	2.00E-06	6.70E-04	6.90E-11	6.80E-07	5.10E-06	1.20E-06	5.40E-04	8.90E-06	3.00E-02	1.80E-06	€ 0.0001	c2	€ 0.0001	Production (A1-A3)	
Insulation	177	Rockwool, cavity wall and curtain wall plates	8.52E-07	7.78E-03	9.44E-01	3.15E-08	2.78E-04	5.19E-03	9.07E-04	1.54E-01	4.26E-03	3.33E+01	1.06E-03	€ 0.0948	c2	€ 0.0948	Production (A1-A3)	
Gypsum		Knauf Gipsvezelplaat 12.5 mm [MRPI]	1.57E-04	1.73E-02	2.31E+00	2.06E-07	1.14E-03	7.79E-03	2.79E-03	1.06E+00	4.43E-02	1.70E+02	2.78E-02	€ 0.2900	c2	€ 0.2900	Production (A1-A3)	per m2 ipv per kg

Figure G.2: LCA input for the production of virgin material life cycle phase.

LCA Database

Totaalprofiel constructiemateriaal — Recycling (D1)

Materiaal	nr.	Materiaalcode en omschrijving	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
S235	E0088	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	4.53E-09	2.56E-04	4.03E-02	6.01E-09	2.71E-05	2.32E-04	5.49E-05	7.27E-03	4.53E-04	1.95E+00	4.03E-05	€ 0.0043	c2	€ 0.0043	Demolition (C1)	1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D
C30/37	WPNL0031	0270-reC&Breken, per kg steenachtig (o.b.v. SBK Breken steenachtig MRPI)	9.69E-10	1.20E-05	1.60E-03	1.85E-10	8.94E-07	7.37E-06	1.66E-06	3.49E-04	5.83E-06	2.23E-02	4.71E-06	€ 0.0002	c3	€ 0.0002	Waste recycling	
Timber	WPNL0045	0284-reC&Verspanen hout (o.b.v. Wood chipping, industrial residual wood, stationary electric chipper {GLO}| market for | Cut-off, U)	5.09E-09	1.01E-04	1.49E-02	7.27E-10	3.75E-06	6.67E-05	7.36E-06	2.73E-03	7.06E-05	3.99E-01	2.77E-05	€ 0.0014	c3	€ 0.0018	Demolition (C1)	Recycling of rebar is taken as recycling concrete (crusher) + recycling steel (remelting)

Figure G.3: LCA input for the recycling life cycle phase.

LCA Database — Demolition (C1,C2)

Materiaal	nr.	Materiaalcode en omschrijving (Totaalprofiel constructiemateriaal)	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
S235	E0088	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	4.53E-09	2.56E-04	4.03E-02	6.01E-09	2.71E-05	2.32E-04	5.49E-05	7.27E-03	4.53E-04	1.95E+00	4.03E-05	€ 0.0043	c2	€ 0.0043	Demolition (C1)	1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D
C30/37	E0073	SBK Demolition concrete (tescop) (NL)	1.45E-08	8.04E-05	1.14E-02	2.06E-09	9.66E-06	7.21E-05	1.57E-05	4.22E-03	8.52E-05	3.00E-01	1.03E-05	€ 0.0014	C3	€ 0.0019		Standard Concrete demolition + 30% added for Cat 3 data.
Rebar	E0088	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	4.53E-09	2.56E-04	4.03E-02	6.01E-09	2.71E-05	2.32E-04	5.49E-05	7.27E-03	4.53E-04	1.95E+00	4.03E-05	€ 0.0043	c2	€ 0.0043	Demolition (C1)	1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D
KPV	E0073	SBK Demolition concrete (tescop) (NL)	1.45E-08	8.04E-05	1.14E-02	2.06E-09	9.66E-06	7.21E-05	1.57E-05	4.22E-03	8.52E-05	3.00E-01	1.03E-05	€ 0.0014	C3	€ 0.0019		Standard Concrete demolition + 30% added for Cat 3 data.
Timber	E0088	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	4.53E-09	2.56E-04	4.03E-02	6.01E-09	2.71E-05	2.32E-04	5.49E-05	7.27E-03	4.53E-04	1.95E+00	4.03E-05	€ 0.0043	c2	€ 0.0043	Demolition (C1)	Chosen due to demolition Environmental impact is mostly due to weight, nog size. This means timber and steel can be compared.

Figure G.4: LCA input for the demolition life cycle phase.

LCA Database — Deconstruction (C1,C2)

Materiaal	nr.	Materiaalcode en omschrijving (Totaalprofiel constructiemateriaal)	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
S235	137	Steel, VanMaastrigt p.133	0.00E+00	1.12E-04	3.40E-02	0.00E+00	3.08E-05	8.75E-05	2.17E-05	3.10E-04	2.50E-05	6.94E-01	1.27E-05	€ 0.0024	C3	€ 0.0031	Deconstruction (C1)	
C30/37	146	Kanaalplaatvloer 200 [MRPI] (1/2*Construction[A5])	3.50E-08	1.45E-03	2.20E-01	2.70E-08	2.20E-04	1.65E-03	3.75E-04	1.70E-01	2.75E-03	1.50E+01	2.75E-04	€ 0.0381	c2	€ 0.0381	Deconstruction (C1)	Schaduwprijs per m2 niet per kg
KPV		Kanaalplaatvloer 200 [MRPI] (1/2*Construction[A5])	3.50E-08	1.45E-03	2.20E-01	2.70E-08	2.20E-04	1.65E-03	3.75E-04	1.70E-01	2.75E-03	1.50E+01	2.75E-04	€ 0.0381	c2	€ 0.0381	Deconstruction (C1)	Schaduwprijs per m2 niet per kg
Timber	137	Steel, VanMaastrigt p.133	0.00E+00	1.12E-04	3.40E-02	0.00E+00	3.08E-05	8.75E-05	2.17E-05	3.10E-04	2.50E-05	6.94E-01	1.27E-05	€ 0.0024	C3	€ 0.0031	Deconstruction (C1)	Same as steel, due to impact depending on weight, not dimensions

Figure G.5: LCA input for the deconstruction life cycle phase.

LCA Database — Disposal (C3,C4)

Materiaal	nr.	Materiaalcode en omschrijving (Totaalprofiel constructiemateriaal)	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
S235	137	Steel, Heavy Construction Products (beams, columns) [BmS 2013]	4.53E-09	2.56E-04	4.03E-02	6.01E-09	2.71E-05	2.32E-04	5.49E-05	7.27E-03	4.53E-04	1.95E+00	4.03E-05	€ 0.0043	c2	€ 0.0043	Demolition (C1)	1 ton heavy construction products consist of 900 kg sections (10% BF and 90% EAF) and 100 kg plate (BF). No coilcoating or hot dip galvanising is included. MRPI-CODE 9.2.00011.004. EPD declares 50% sec. content, not calculated because it's part of the karakterised results voor module C-D
C30/37	WPNL0003	sto&Stort beton, cellenbeton (o.b.v. Waste concrete {Europe without Switzerland}| treatment of waste concrete, inert material landfill | Cut-off, U)	6.10E-09	7.27E-05	5.34E-03	1.77E-09	5.66E-06	3.95E-05	7.46E-06	2.18E-03	5.42E-05	1.86E-01	6.45E-06	€ 0.0007	C3	€ 0.0009	Disposal (C4) [Landfill]	Standard Concrete waste + 30% added for Cat 3 data.
Timber	WPNL0009	0246-sto&Stort hout, geschilderd (o.b.v. 99% Waste wood, untreated en 1% Waste paint {EU}| treatment of, sanitary landfill | Cut-off, U)	1.42E-08	1.24E-04	7.58E-02	2.69E-09	2.39E-05	7.25E-05	2.89E-05	5.50E-03	1.18E-04	4.27E-01	2.03E-05	€ 0.0049	C3	€ 0.0064	Disposal (C4) [Landfill]	
Insulation	WPNL0009	0250-sto&Stort minerale wol (o.b.v. Waste mineral wool, for final disposal {Europe without Switzerland}| treatment of waste mineral wool, inert material landfill | Cut-off, U)	6.10E-09	7.27E-05	5.34E-03	1.77E-09	5.66E-06	3.95E-05	7.46E-06	2.18E-03	5.42E-05	1.86E-01	6.45E-06	€ 0.0007	C3	€ 0.0009	Disposal (C4) [Landfill]	
Gypsum		Knauf Gipsvezelplaat 12.5 mm [MRPI]	6.12E-09	9.91E-05	1.20E-02	2.12E-09	1.27E-05	8.56E-05	1.92E-05	8.29E-03	1.69E-04	7.93E-01	2.44E-05	€ 0.0020	c2	€ 0.0020	Disposal (C3,C4,D)	per m2 ipv per kg

Figure G.6: LCA input for the disposal life cycle phase.

LCA Database			Incineration (C1)															
Totaalprofiel constructiemateriaal			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
Materiaal	nr.	Materiaalcode en omschrijving	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
Timber	WPNL0026	0263-avC&Verbranden hout, verontreinigd (13,99 MJ/kg) (o.b.v. Waste building wood, chrome preserved {CH}| treatment of, municipal incineration | Cut-off, U)	1.97E-08	5.19E-05	9.36E-03	1.06E-09	4.08E-05	2.14E-04	5.56E-05	2.54E-02	1.12E-03	6.16E-01	2.68E-05	€ 0.0042	C3	€ 0.0055	Incineration (C4)	per kg
Fossil	E0080	0267-avD&Vermeden energieproductie AVI, o.b.v. FOSSIELE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	2.68E-09	3.78E-04	4.14E-02	4.76E-09	5.84E-06	2.70E-05	3.98E-06	2.11E-03	2.43E-05	1.11E-01	6.68E-06	€ 0.0025	C3	€ 0.0032	Energy	per MJ LHV. Negative burden due to avoided emissions of energy production
Renewable	E0081	0268-avD&Vermeden energieproductie AVI, o.b.v. HERNIEUWBARE grondstoffen, 18% elektrisch en 31% thermisch (per MJ LHV)	6.67E-09	1.69E-05	3.10E-03	1.01E-09	1.28E-05	8.22E-05	2.68E-05	6.99E-03	1.55E-04	1.58E-01	4.77E-05	€ 0.0014	C3	€ 0.0018	Energy	per MJ LHV. Negative burden due to avoided emissions of energy production

Figure G.7: LCA input for the incineration life cycle phase.

LCA Database			Transport (A4, C2, D)															
Totaalprofiel constructiemateriaal			€ 0.16	€ 0.16	€ 0.05	€ 30.00	€ 0.06	€ 4.00	€ 9.00	€ 0.09	€ 0.03	€ 0.00	€ 0.06					
Materiaal	nr.	Materiaalcode en omschrijving	Uitputting abiotische grondstoffen - ADP	Uitputting fossiele energiedragers-ADP	Klimaatsverandering - GWP 100 j.	Aantasting ozonlaag - ODP	Fotochemische oxydantvorming - POCP	Verzuring - AP	Vermesting - EP	Humane toxiciteit - http	Zoetwater aquatische ecotoxiciteit - FAETP	Maritieme aquatische ecotoxiciteit - MAETP	Terrestrische ecotoxiciteit - TETP	Schaduwprijs excl.	Categorie / waarden getoetst?	Schaduwprijs incl.	Process used	Extra information
Ship	T0008	Transoceanic freight ship	2.49E-09	7.82E-05	1.14E-02	1.80E-09	1.23E-05	2.38E-04	2.12E-05	5.10E-03	9.00E-05	4.36E-01	1.64E-05	€ 0.0022		€ 0.0022	Transport	tkm
Lorry	T0001	Lorry (Truck), unspecified (default)	3.75E-07	9.72E-04	1.32E-01	2.43E-08	7.77E-05	5.71E-04	1.14E-04	5.27E-02	1.55E-03	5.58E+00	1.87E-04	€ 0.0154		€ 0.0154	Transport	tkm (loaded to customer and empty return. One way distance should be used.)

Figure G.8: LCA input for the transport for every life cycle phase.

Transport Distances			
Material	**impact**	**LCA Stage**	**Distance [km]**
S235	Virgin	A2-Ship	23600
	Virgin	A4-Lorry	130
	Recycle	C2-Ship	16520
	Reuse	D4-Lorry	50
KPV	Virgin	A4-Lorry	80
	Recycle	D4-Lorry	50
	Reuse	D4-Lorry	50
	Disposal	C2-Lorry	50
C30	Virgin	A4-Lorry	80
	Recycle	D4-Lorry	50
	Reuse	D4-Lorry	50
	Disposal	C2-Lorry	100
Rebar	Virgin	A4-Lorry	120
	Recycle	C2+D2+D4-Lorry	350
Timber	Virgin	A4-Lorry	80
	Recycle	D4-Lorry	50
	Reuse	D4-Lorry	50
	Landfill	C2-Lorry	100
	Incineration	C2-Lorry	150
Insulation	Virgin	A4-Lorry	80
	Landfill	C2-Lorry	100

Figure G.9: Transport distances per life cycle phase per material.

Input parameters						
	Steel	**Hollo-core Slab**	**Rebar**	**Concrete**	**Glulam**	**Insulation**
R1	0.51	0.02	0.53	0.02	0	0
R2	0.91	0.8	0.95	0.8	0	0
R4	0.04	0	0	0	0	0
R5	0.08	0	0	0	0	0
k_rec	1	0.06	1	0.06	0.05	0
k_reu	0.8	0.8	0	0.8	0.5	0
p_s	0.32	0	0	0	0	0
k_s	0.10	0	0	0	0	0
P_r4	0.75	0.2	0.75	0.2	0.5	0
P_r5	0.75	0.2	0.75	0.2	0.5	0
BCI	0.76	0.21	0.21	0.21	0.6	0
TSL	150	150	150	150	75	30
R3	0	0	0	0	0.8	0
LHV	0	0	0	0	13.99	0
%renewable	0	0	0	0	0.09	0

Figure G.10: Summarized input parameters for the end–of–life allocation scenarios, described per material.

H | GRASSHOPPER INPUT

H.1 TOTAL SCRIPT

The total Grasshopper script is shown in Figure H.1. The classification of the script corresponds to the schematization as found in the research approach of Figure 2.3. The script is divided into six main phases, each time completing a different part of the calculation. The following phases can be distinguished:

1. Input
2. Geometry + Structural Calculation
3. Bill of Materials
4. Life Cycle Assessment
5. End–of–Life scenarios
6. Output

Each main phase is divided into different groups that calculate a certain part of the phase concerned.

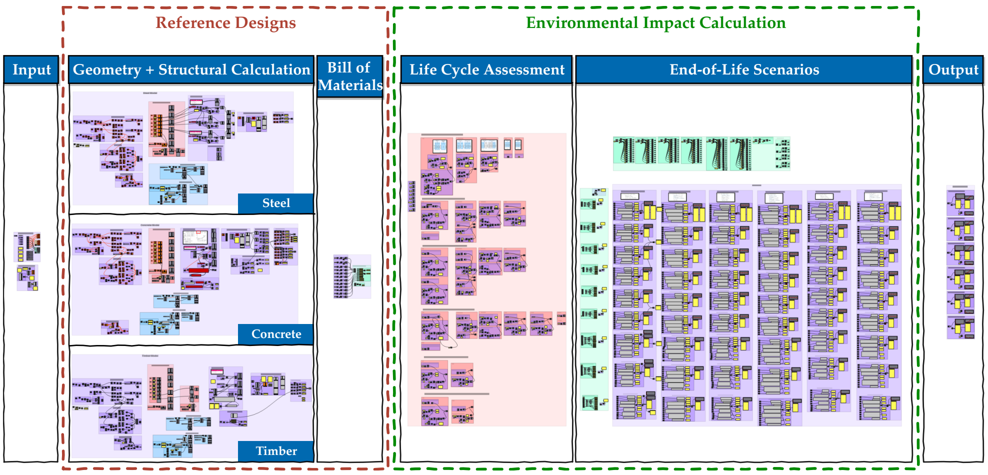


Figure H.1: Total parametric model, as constructed to calculate the environmental impact in the early design phase.

A general flow of the total grasshopper script is shown in Figure H.2. Numbers correspond to the groups as menstioned in the caption. Every number dotted number refers to specific group which is elaborated elaborated in section H.2 until H.6. For clarification reasons, some groups are not numbered and linked. In the LCA group ((10) — (14)) only the full flow of glued laminated timber is shown ((10) — (14)) while for the other materials, only the virgin impact number is shown ((10)). The same is done for the scenarios, where only the calculation of scenario 4 is shown ((17)).

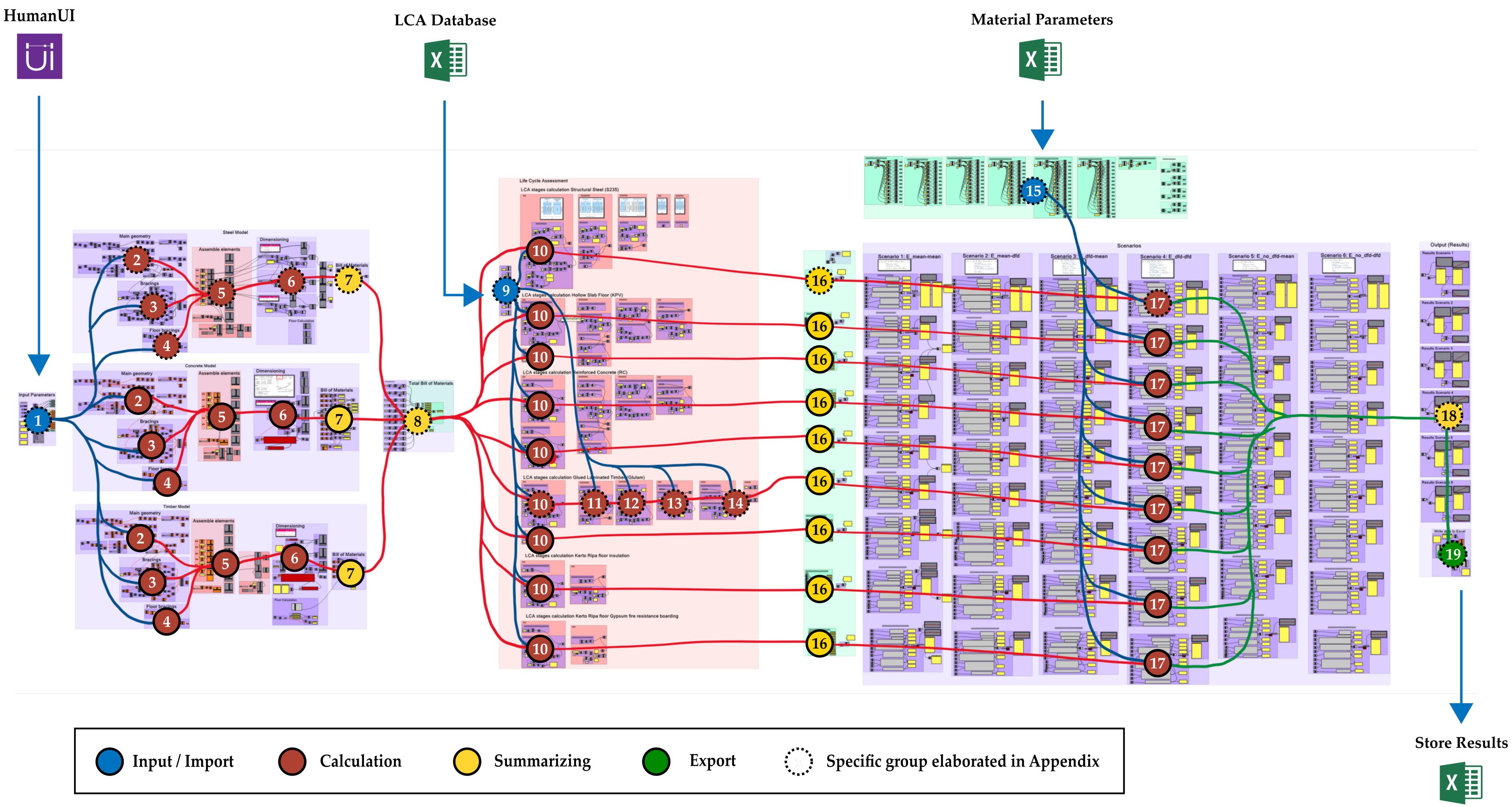


Figure H.2: Total parametric script including numbers per grasshopper group: (1) = Input Parameters (2) = Structural Framework (nodes, beams and columns), (3) = Bracings, (4) = Floor Bracings, (5) = Element Assembly, (6) = Dimensioning of structural members, (7) = Bill of Materials per design, (8) = Total Bill of Materials, (9) = LCA Database (Excel Import), (10) = Virgin material impact, (11) = Recycling impact, (12) = Reuse impact, (13) = Disposal of material impact, (14) = Incineration impact, (15) = Input Parameters for scenarios, (16) = Impact factors (summed up LCA), (17) = Scenario equations, (18) = Results per scenario and (19) = Export results to Excel.

H.2 INPUT

The input parameters group collects all input data necessary for the parametric script. In this group, the Excel files are loaded and all variable input parameters are summed up. These parameters enter a stream gate in which they are guided into the currently selected reference design. This means the three reference designs are calculated separately.

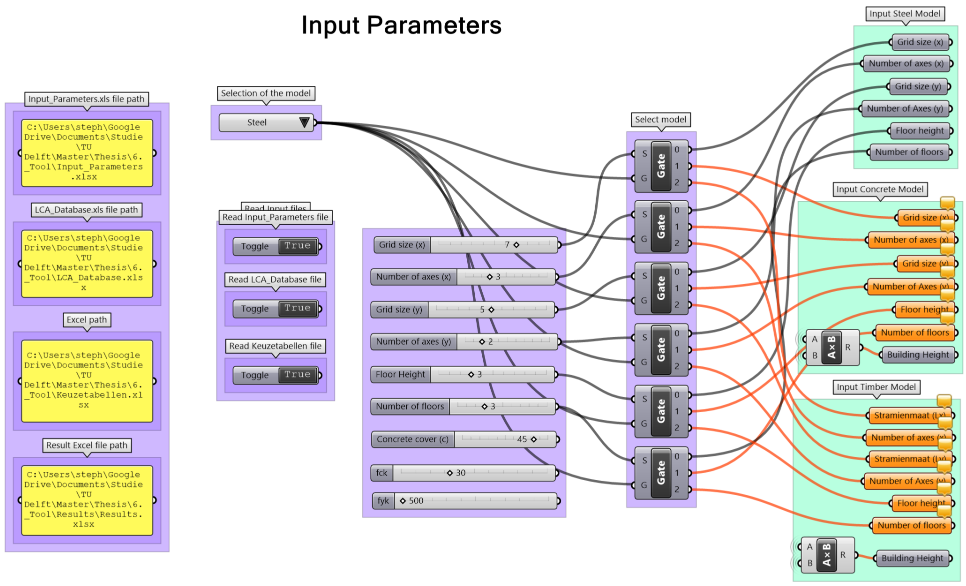


Figure H.3: Grasshopper input phase, corresponding to 1 of Figure H.2.

H.3 REFERENCE DESIGNS

Every reference design has it's own geometrical and structural build–up. This means the model as shown in Figure H.4 exists for concrete and timber as well.

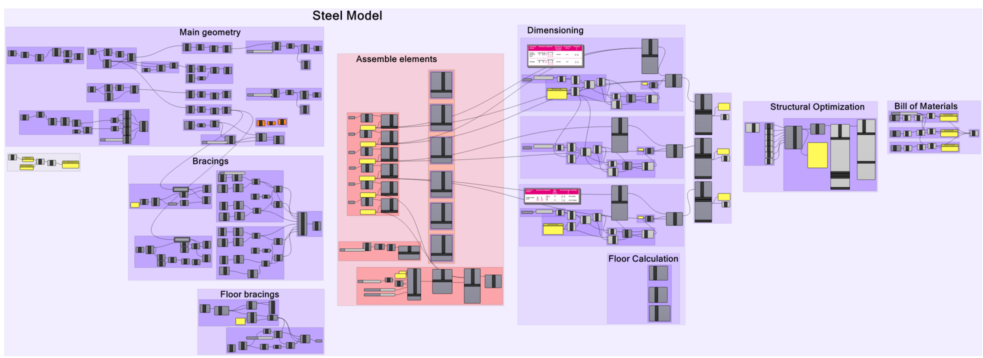


Figure H.4: Steel reference designs phase

H.3.1 Geometry

The geometry is divided in a general structural framework, bracings and floorbracings part.

H.3.1.1 *Structural Framework*

The framework constructs a 3D grid and connects the nodes in order to create columns, beams and sleepers in Figure H.5.

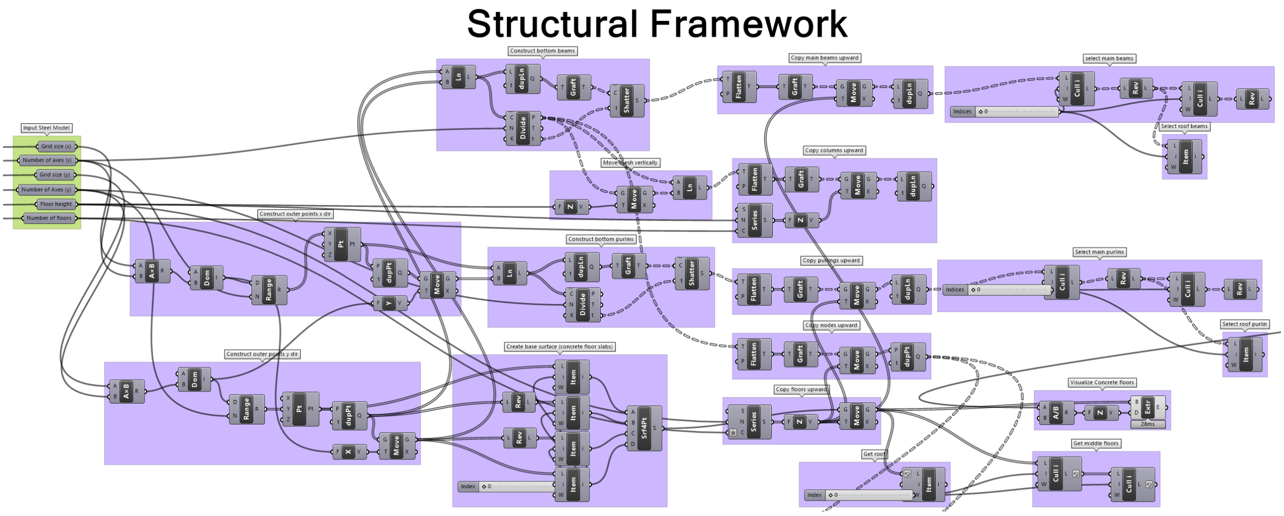


Figure H.5: Grasshopper structural framework group, corresponding to 2 of Figure H.2.

H.3.1.2 *Bracings*

The framework is braced vertically by connecting outer nodes diagonally in Figure H.6

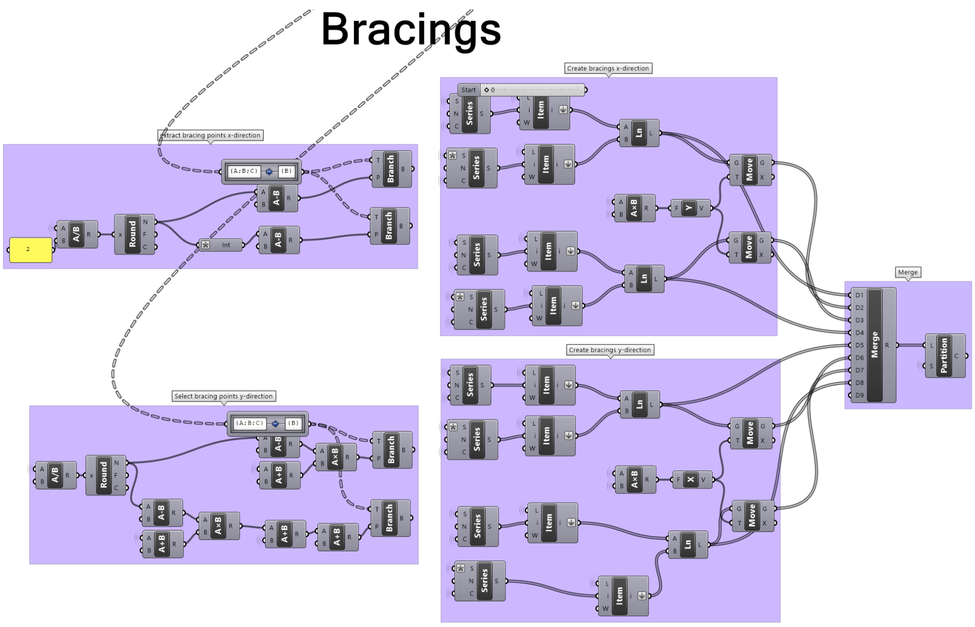


Figure H.6: Grasshopper bracings group, corresponding to 3 of Figure H.2.

H.3.1.3 *Floor bracings*

The floor bracings ensure the rotational stability of the structure, as shown in Figure H.7. In real life this is accomplished by the diaphragm action of the hollow–core slabs but this is modeled by floor braces.

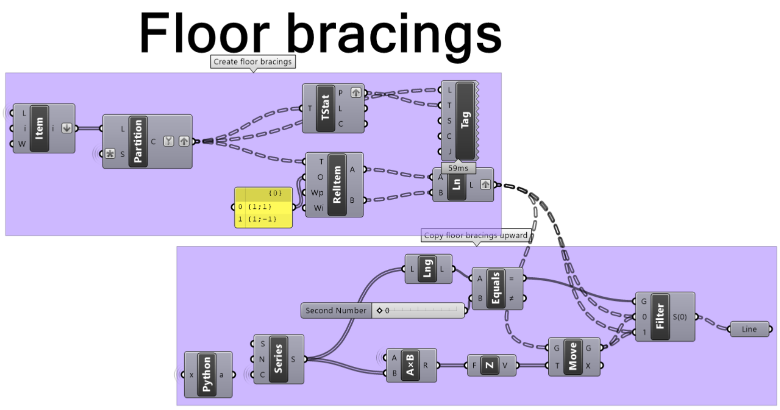


Figure H.7: Grasshopper floor bracings group, corresponding to 4 of Figure H.2.

H.3.2 Structural Calculation

The structural calculation is divided into three groups; the element assembly, dimensioning of structural elements and the bill of materials for the corresponding material.

H.3.2.1 *Element assembly*

The element assembly script, visualized in Figure H.8, divides the lines constructed by the geometric structural framework Figure 3.2a into six groups; roofbeams, beams, sleepers, columns, bracings and floorbracings, whereafter the elements are created per group. Every node of the framework is modeled as a hinged connection and the supports are modeled as well. At last, the materials neccesary for every structural design are created.

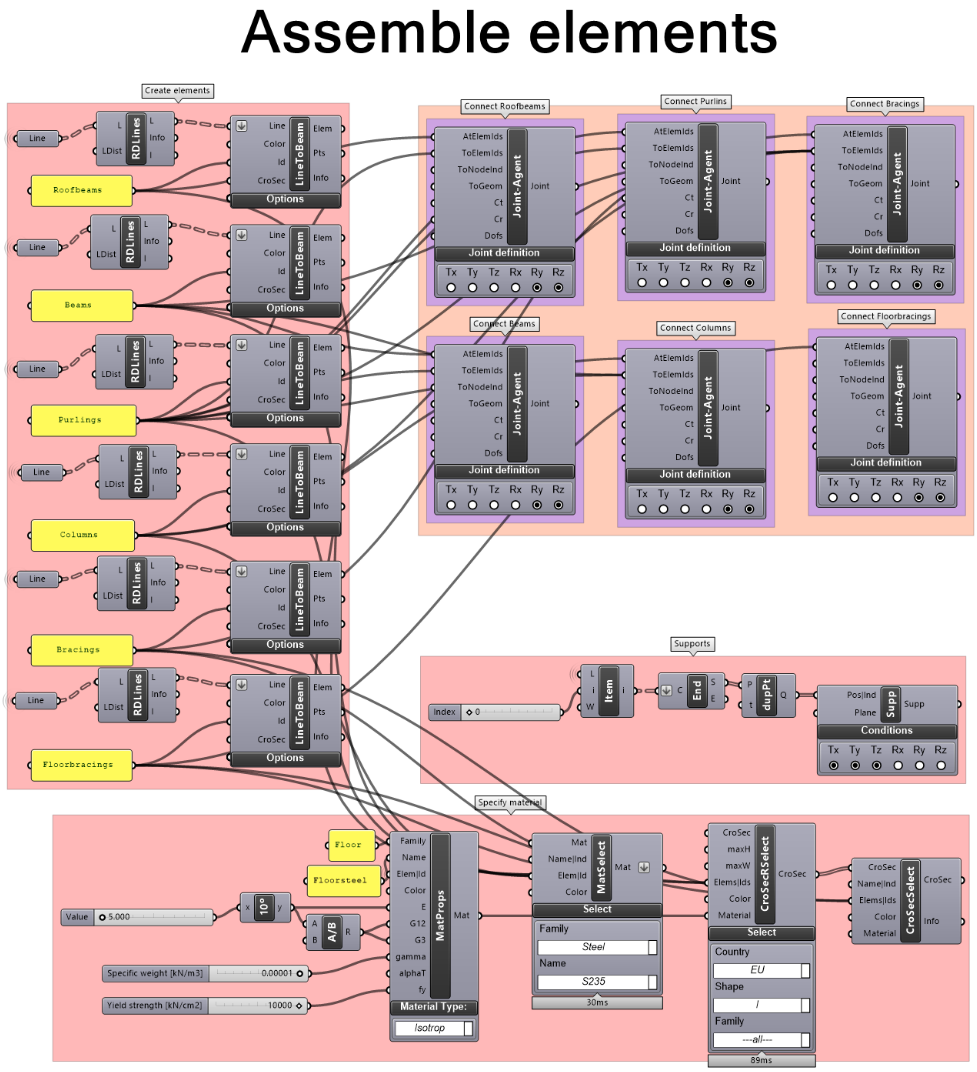


Figure H.8: Grasshopper element assembly group, corresponding to (5) of Figure H.2.

H.3.2.2 *Dimensioning*

After the element assembly, every element group is dimensioned based on the rules of thumb as shown in Table 3.5.

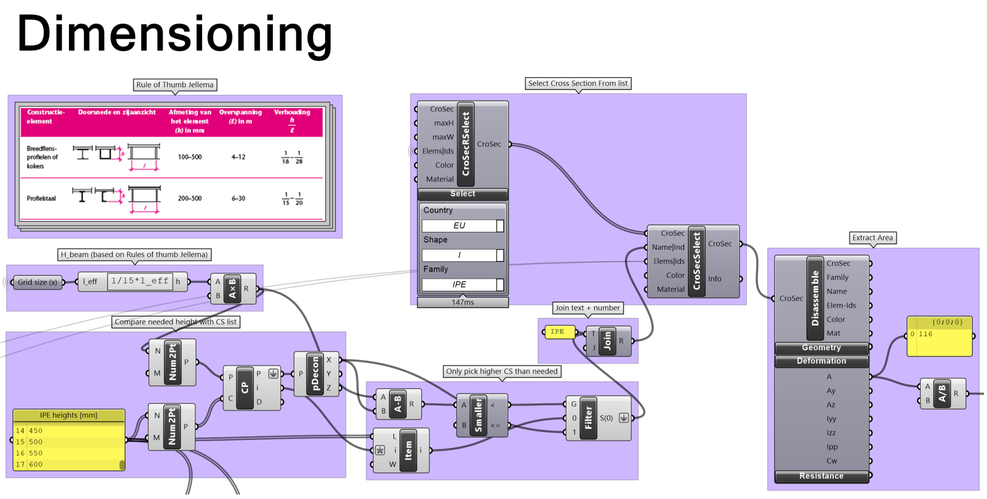


Figure H.9: Grasshopper dimensioning group, corresponding to (6) of Figure H.2.

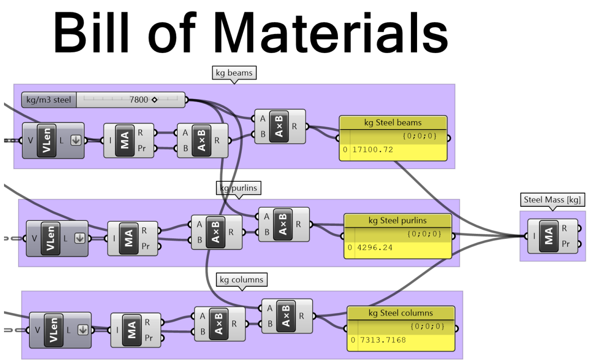


Figure H.10: Grasshopper bill of materials of the steel design group, corresponding to (7) of Figure H.2.

H.4 BILL OF MATERIALS

At last, the Bill of Materials (BoM) is created by summing up the weights per element group. This procedure is executed for every material of every reference design, see Figure H.10, wherafter a total Bill of Materials is constructed Figure H.11.

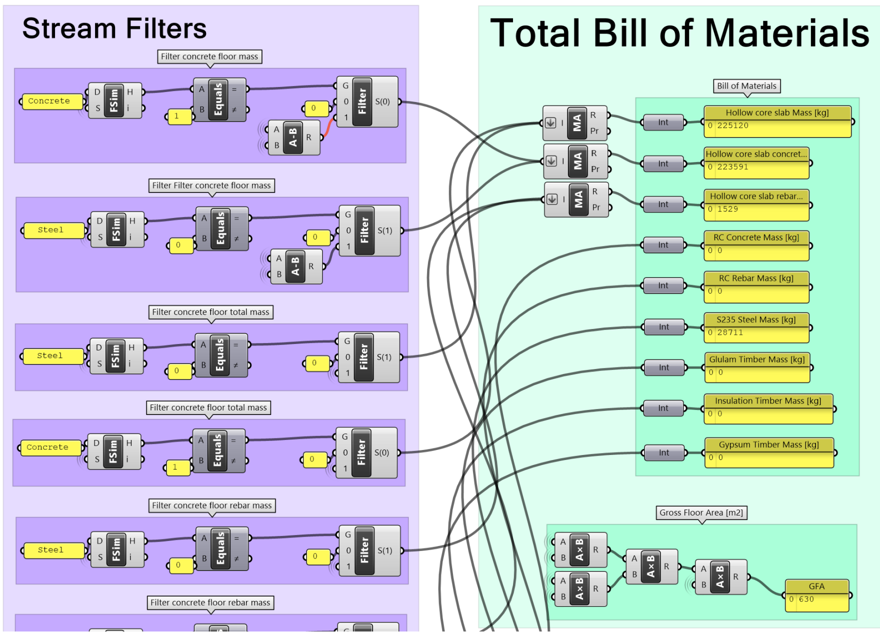


Figure H.11: Grasshopper total Bill of Materials phase, corresponding to (8) of Figure H.2.

H.5 ENVIRONMENTAL IMPACT CALCULATION

H.5.1 Life Cycle Assessment

The LCA is modeled in Grasshopper per material and per life cycle phase. This can be seen as a matrix with the columns being the different life cycle phases and the rows being the different materials. Every cell then represents the combination of a certain row (material) and column (life cycle phase). This setup is shown in Table 4.4.

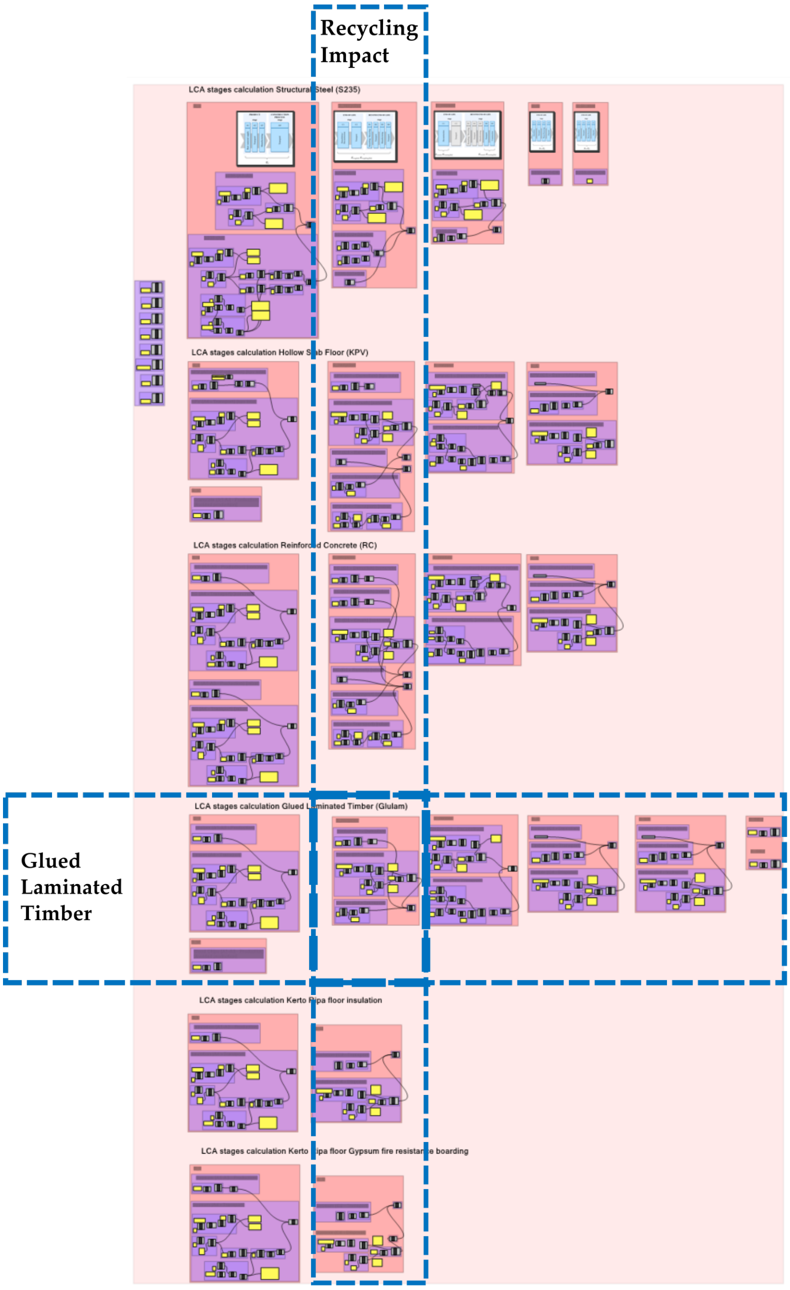


Figure H.12: Grasshopper Life Cycle Assessment phase

First, the necessary excel files are loaded in Figure H.13. This database includes the Excel tables found in Figure G.2, G.3, G.4, G.5, G.6, G.7, G.8 and G.9. These LCA data combined results in the different environmental impacts per category, as shown in the next subsections.

H.5.1.1 *LCA database files*

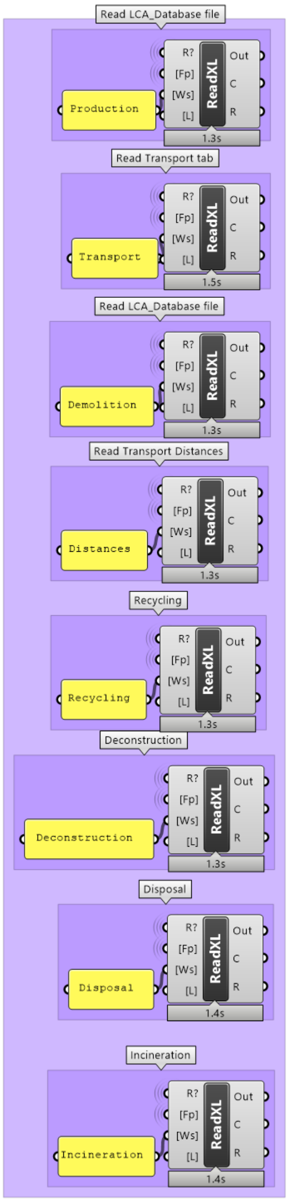


Figure H.13: Grasshopper LCA database group, corresponding to (9) of Figure H.2.

H.5.1.2 *Virgin material impact*

The environmental impact of every life cycle phase is calculated in the same manner. The left part of Figure H.14 shows which life cycle stages are included in the virgin impact calculation. These stages are then summed up on the right side of the figure. The production directly comes from the Excel table of Figure G.2, whereas the transport is a combined value of the transport impact (Figure G.8 multiplied with the transport distance (Figure G.9). The exact procedure of every life cycle calculation is elaborated in Appendix F.

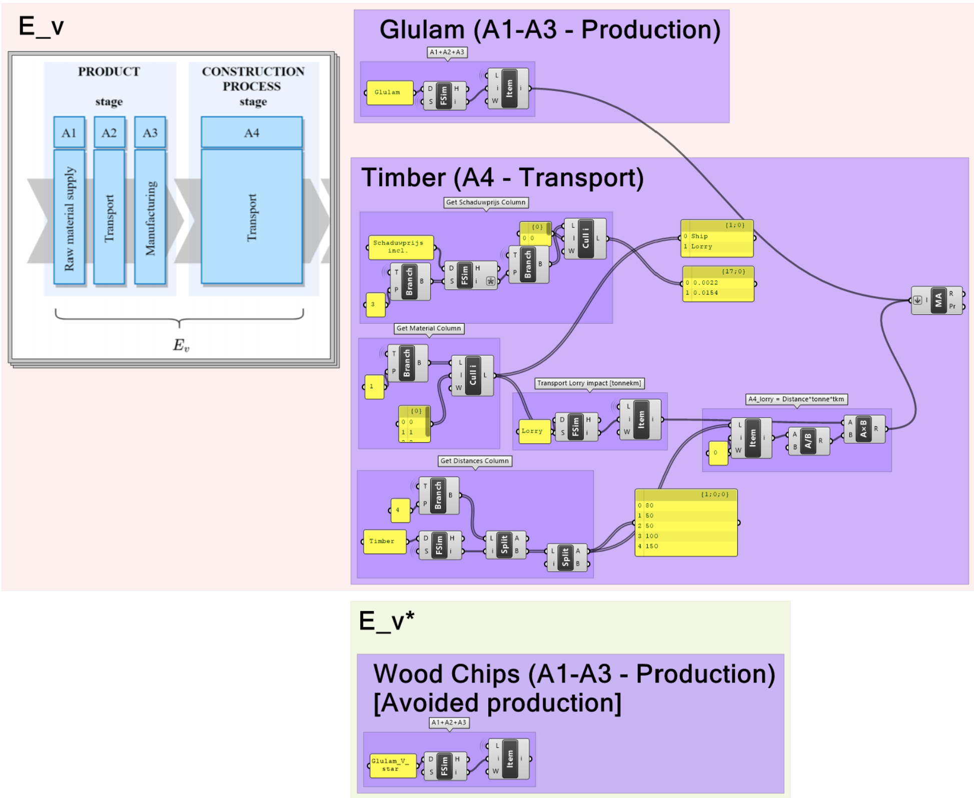


Figure H.14: Grasshopper Virgin material Environmental Impact Group of Glued Laminated Timber, corresponding to (10) of Figure H.2.

H.5.1.3 *Recycling impact*

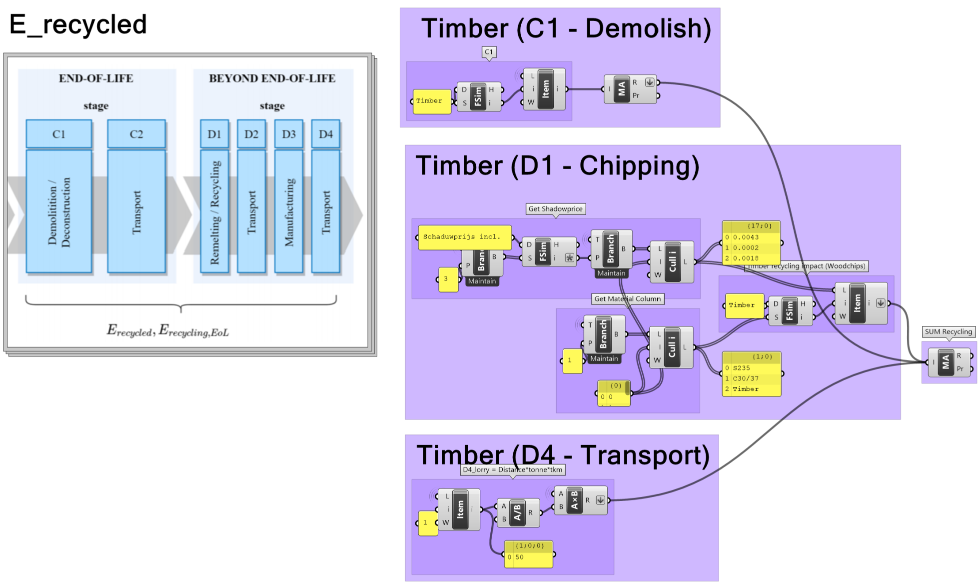


Figure H.15: Grasshopper Recycled material Environmental Impact Group of Glued Laminated Timber, corresponding to (11) of Figure H.2.

H.5.1.4 *Reuse impact*

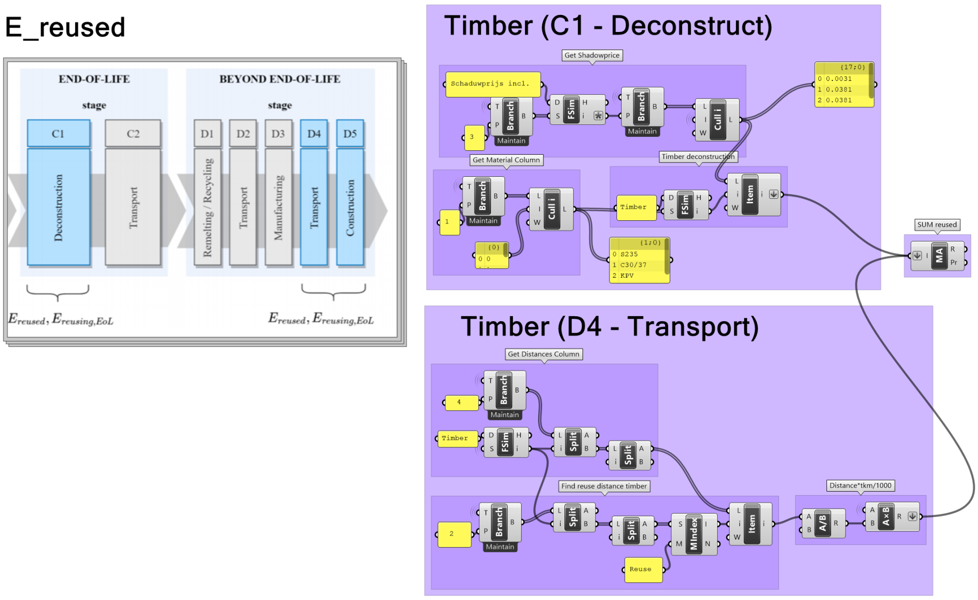


Figure H.16: Grasshopper Reused material Environmental Impact Group of Glued Laminated Timber, corresponding to (12) of Figure H.2.

H.5.1.5 *Disposal impact*

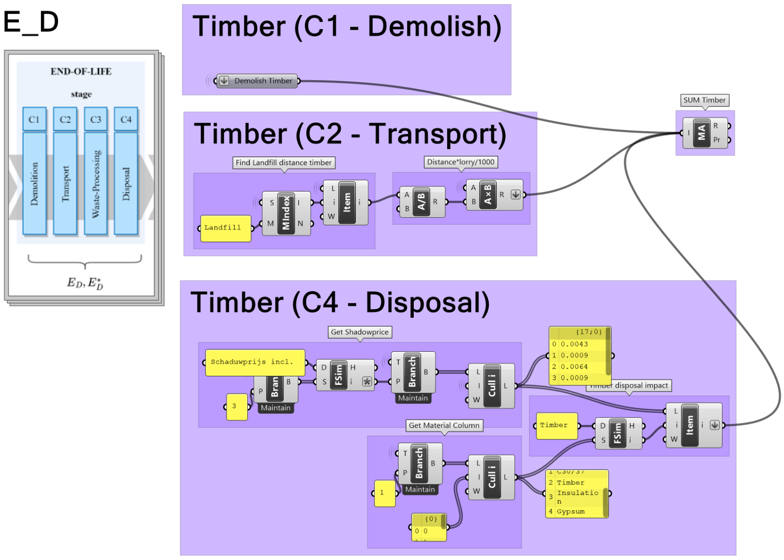


Figure H.17: Grasshopper Disposed material Environmental Impact Group of Glued Laminated Timber, corresponding to (13) of Figure H.2.

H.5.1.6 *Incineration impact*

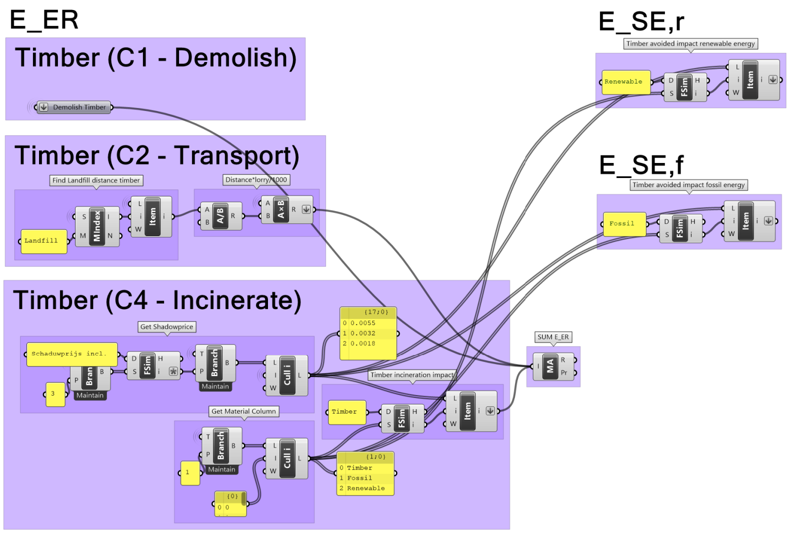


Figure H.18: Grasshopper Incinerated material Environmental Impact Group of Glued Laminated Timber, corresponding to (14) of Figure H.2.

H.5.2 End–of–Life allocation Scenarios

The six end–of–life allocation equation scenarios are implemented in the following manner. Initially, the different input parameters as shown in Table 4.5 are imported from Excel (upper green area in Figure H.19 and shown in Figure H.20). Then, the results of the Life Cycle Assessment of subsection H.5.1 are summarized per material as Environmental Impact Factors (left green area in Figure H.19 and Figure H.21). Subsequently, the impact factors and the input parameters are combined in the end—of-–life equations. These equations iterate over a lifespan of 170 years, calculating the environmental impact of a specific material for a specific scenario from a lifespan of 1 — 170 years.

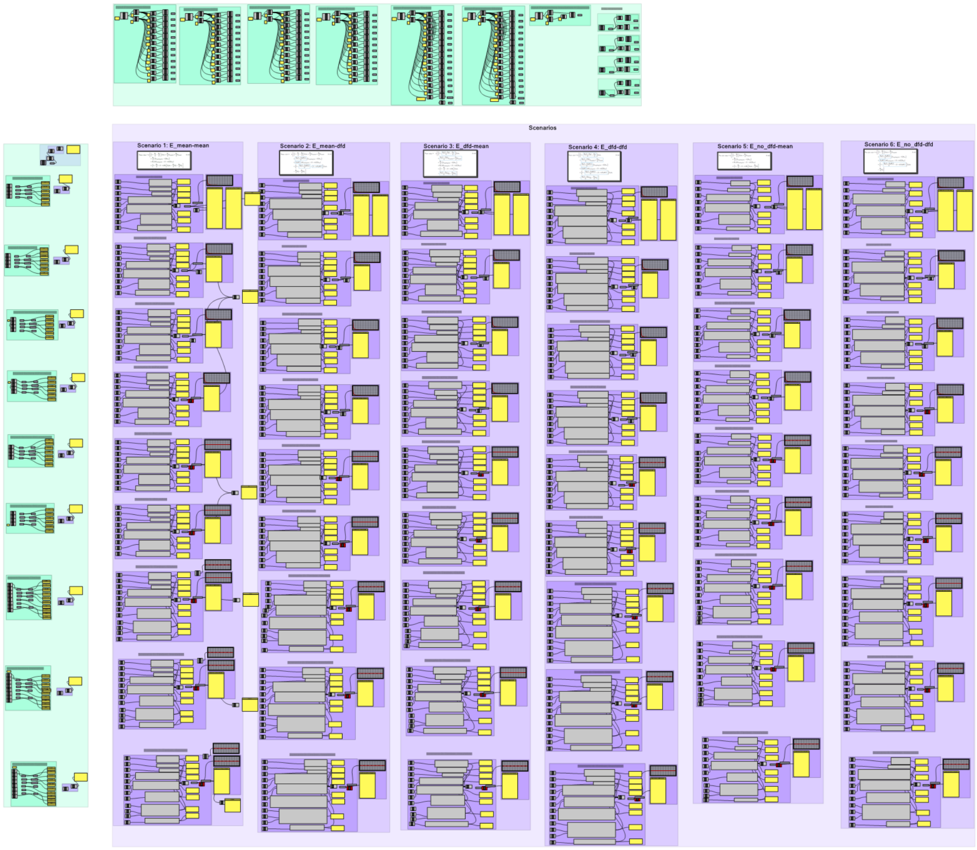


Figure H.19: Grasshopper End–of–Life Scenarios phase

H.5.2.1 *Input parameters*

For every material, the input parameters which have been derived in Appendix F are imported from Excel.

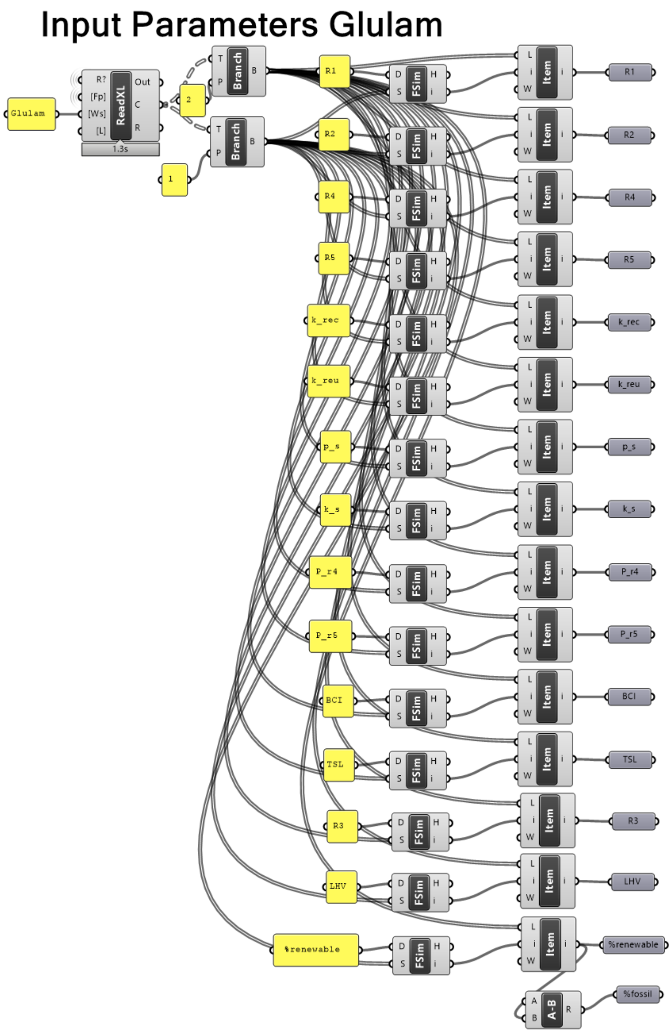


Figure H.20: Grasshopper Input Parameters group for the end–of–life scenarios, corresponding to (15) of Figure H.2.

H.5.2.2 *Impact factors and Scenario equations*

In Figure H.21, only the group where the environmental impact of steel for scenario 1 is calculated is shown. On the left side, the environmental impact factors are shown, which are the results from the LCA mentioned before. The middle group calculates the environmental impact per life cycle phase. Every equation (grey block) corresponds to a certain life cycle phase, and has both the impact factors (shown on the left) as the input parameters (Figure H.20) as input. On the right side, the separate environmental impact is summed up such that the total environmental impact for a certain material for every possible lifespan is shown.

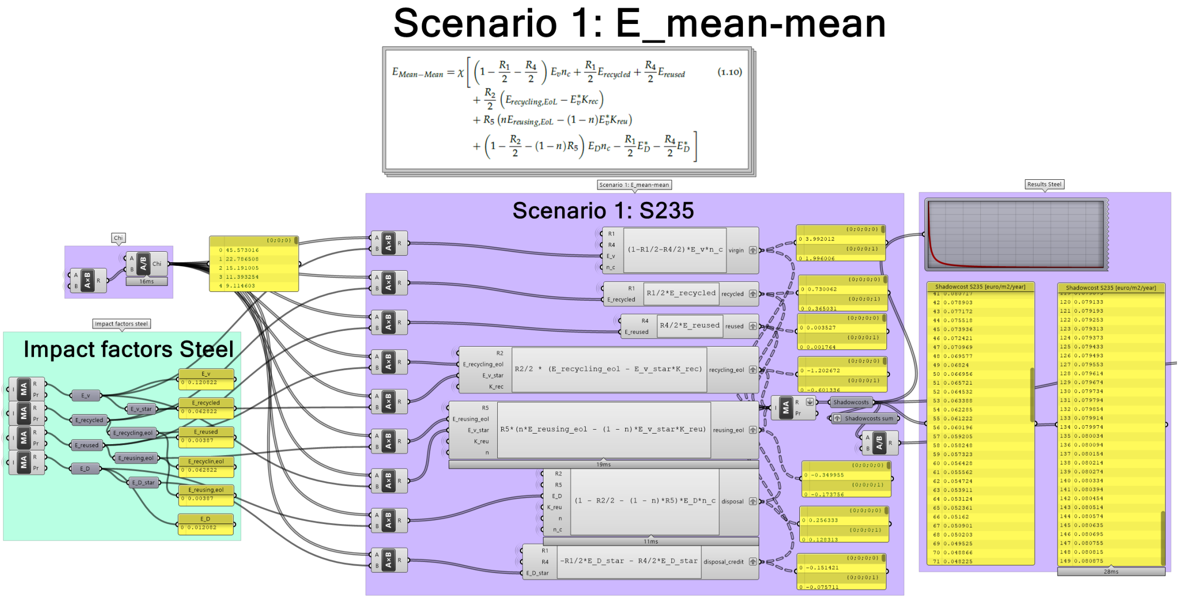


Figure H.21: Grasshopper Impact factors and scenario equations group, corresponding to 16 and 17 of Figure H.2.

H.6 OUTPUT

The result tab exists of two main tabs. First, the results of every material are summed up for a certain scenario. This is done in Figure H.22. This is done for every scenario, which results in six lists of results. Then, these results are all exported to Excel in Figure H.23 for a specific reference design.

H.6.1 Results per scenario

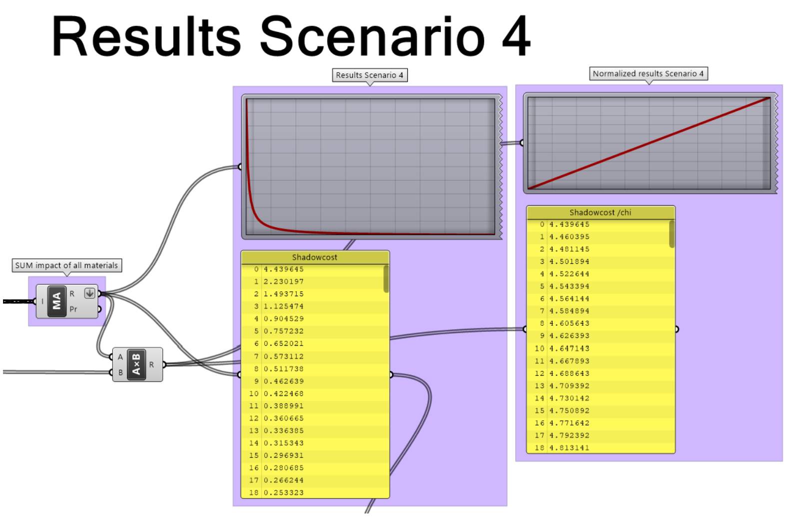


Figure H.22: Results of scenario 4, summarized in a list and corresponding to 18 of Figure H.2.

H.6.2 Export to Excel

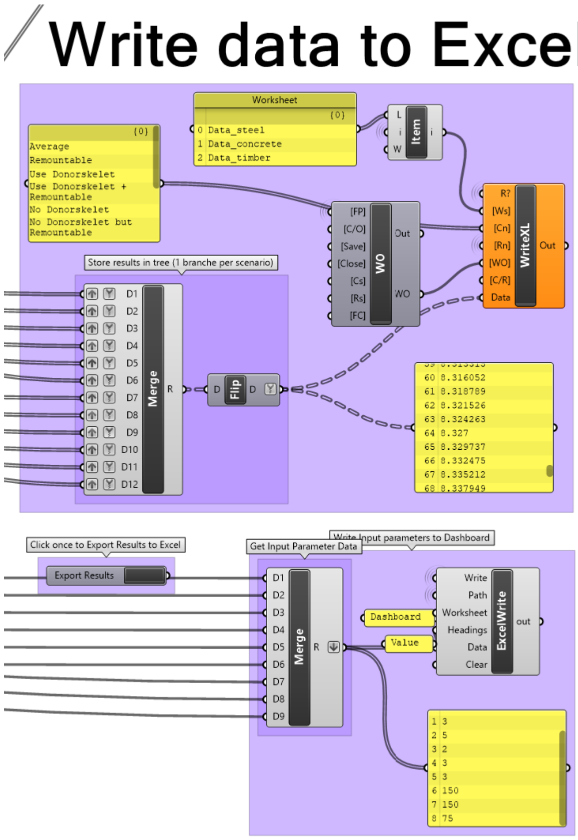


Figure H.23: The summarized results of Figure H.21 are exported to Excel, corresponding to 19 of Figure H.2.

I PARAMETRIC MODEL VALIDATION

I.1 VALIDATION OF THE STRUCTURAL CALCULATION

I.1.1 Steel design

I.1.1.1 *Calculation principles*

Figure I.1 shows the principles that serve as input for the validation of the steel beam in MatrixFrame. The different considered load combinations for both ULS and SLS are shown here. Then the m^2 floor package was calculated, after which converted to a line load on the steel beam. The cross–section is checked on strength and deflection accordingly.

Middle beam middle floor Steel

Consequence Class: CC2

ULS	SLS
LC1: 1.2*Gk + 1.5*Qk	LC3: 1.0*Gk + 1.5*Qk
LC2: 1.35*Gk + 0.5*Qk	LC4: 0.0*Gk + 1.0*Qk

Material Properties	
Section:	IPE500
Strength class:	S355

Middle floor								
Screed	=	1.00 kN/m²						
Hollow core slab VBI150	=	2.68 kN/m²						
Installations	=	0.25 kN/m²						
Suspended ceiling	=	0.25 kN/m²						
Gk,floor	=	4.18 kN/m²						
Live load	=	2.5 kN/m²	ψ_0 =	0.50	ψ_1 =	0.50	ψ_2 =	0.30

Line loads			
Beam: IPE500	Beam span = 7 m	Floor span = 5 m	
Gk,beam	=		0.9 kN/m
Gk,total	=	4.18*5 + 0.9 =	21.8 kN/m
Qk,total	=	2.5*5 =	12.5 kN/m

Load Combinations					
LC1: qd	=	1.2*21.8 + 1.5*12.5 =	**44.9 kN/m**	ULS	Strength
LC2: qd	=	1.35*21.8 + 0.5*12.5 =	35.68 kN/m		
LC3: qd	=	1.0*21.8 + 1.0*12.5 =	**34.3 kN/m**	SLS	Total deflection
LC4: qd	=	1.0*12.5 =	**12.5 kN/m**	SLS	Additional deflection requirement

Figure I.1: Weight calculation of the steel middle beam on the middle floor.

I.1.1.2 *Validation rule of thumb*

ULS: Strength requirement

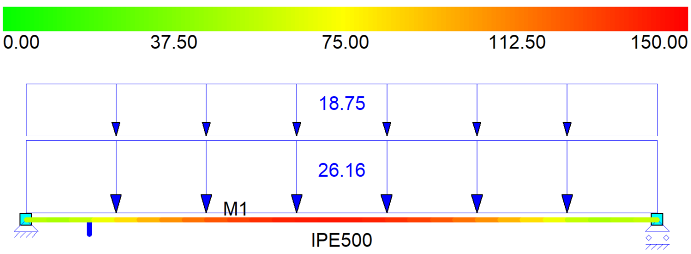


Figure I.2: MatrixFrame result of strength calculation of LC1. Colors reflect the stresses σ_{hh}.

$$u.c. = \frac{\sigma_{hh}}{f_y} = \frac{150}{355} = 0.42 \tag{I.1}$$

The steel beam fulfills the unity check ¡ 1 on strength. A unity check of 0.64 is low, but expected in the early design phase calculations. Moreover, the maximum additional deflection is checked as well.

SLS: Additional deflection requirement

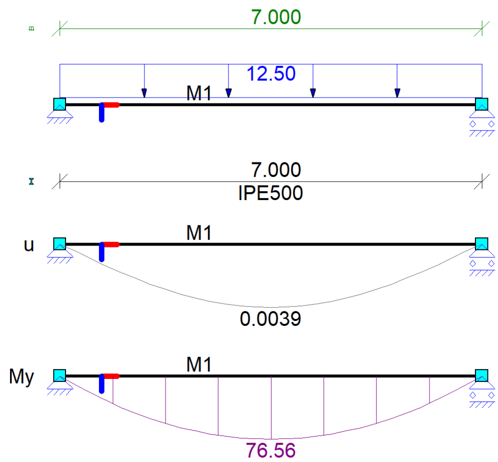


Figure I.3: MatrixFrame result of the above input, calculated with SLS Load Combination 4 (LC4).

$$u_{additional} = 0.0039\ m \tag{I.2}$$

$$u.c. = \frac{u_{additional}}{0.004 \cdot L} = \frac{0.0039}{0.004 \cdot 7} = 0.14 \tag{I.3}$$

The steel beam fulfills the unity check on additional deflection as well.

I.1.2 Timber design

I.1.2.1 *Calculation principles*

Figure I.4 shows the principles that serve as input for the validation of the steel beam in MatrixFrame. The same principles as in the steel calculation are used. Only the values have changed. A glulam cross-section of $bxh = 110x500mm$ is used.

Middle beam middle floor Timber

Consequence Class: CC2

UGT	**BGT**
LC1: 1.2*Gk + 1.5*Qk	LC3: 1.0*Gk + 1.5*Qk
LC2: 1.35*Gk + 0.5*Qk	LC4: 0.0*Gk + 1.0*Qk

Material Properties	
Section Properties	
b =	110 mm
h =	500 mm
Strength class:	GL28h

Middle floor		
Buildup weight (insulation)	=	0.41 kN/m²
Kerto Ripa T508 (t=313mm)	=	0.29 kN/m²
Installations	=	0.25 kN/m²
Suspended ceiling	=	0.25 kN/m²
Gk,total	=	1.21 kN/m²
Live load	=	2.5 kN/m²

ψ_0 = 0.50 ψ_1 = 0.50 ψ_2 = 0.30

Line loads			
Beam: Glulam 495x115	Beam span = 7 m	Floor span = 5 m	
gamma	=	4.6 kN/m3	
Gk,beam	=	0.495*0.115*4.6 =	0.26 kN/m
Total			
Gk,total	=	1.21*5 + 0.26 =	6.3 kN/m
Qk,total	=	2.5*5 =	12.5 kN/m

Load Combinations					
LC1: qd	=	1.2*6.3 + 1.5*12.5 =	**26.31 kN/m**	ULS	Strength
LC2: qd	=	1.35*6.3 + 0.5*12.5 =	14.76 kN/m		
LC3: qd	=	1.0*6.3 + 1.0*12.5 =	**18.8 kN/m**	SLS	Total deflection
LC3: qd	=	1.0*12.5 =	**121.5 kN/m**	SLS	Additional deflection requirement

Figure I.4: Weight calculation of the timber middle beam on the middle floor.

I.1.2.2 *Validation original rule of thumb*

ULS: Strength requirement

As shown in Figure I.5 and Equation I.4, the original rule of thumb as implemented in the model does not comply the strength requirements.

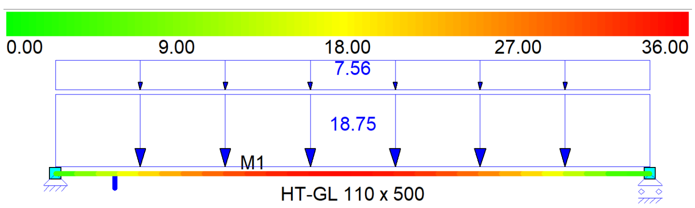
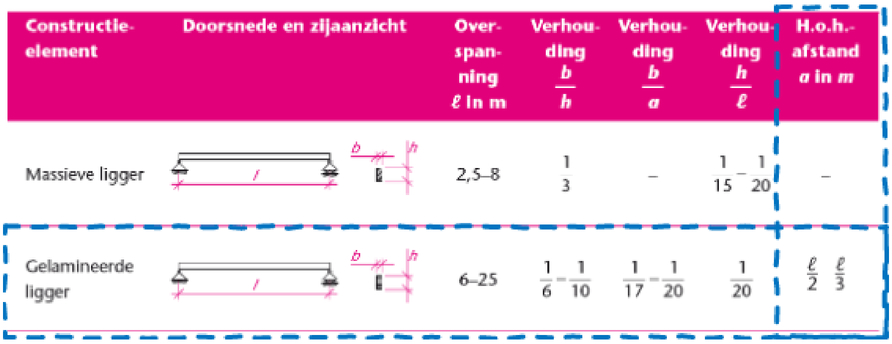


Figure I.5: MatrixFrame result of strength calculation of LC1. Colors reflect the stresses σ_{hh}.

$$u.c. = \frac{\sigma_{hh}}{f_{m,k} \cdot k_{mod}} = \frac{36}{28 \cdot 0.9} = 1.43 \tag{I.4}$$

The original rule of thumb, $h = \frac{L}{15}$, is originally intended for the use with a center distance of $l/2$, see Figure I.6. However, this is not the case in the reference designs, as the center distance is 5 m. For this reason, the original rule of thumb is modified in subsubsection I.1.2.3.



Constructie-element	Doorsnede en zijaanzicht	Over-spanning ℓ in m	Verhouding $\frac{b}{h}$	Verhouding $\frac{b}{a}$	Verhouding $\frac{h}{\ell}$	H.o.h.-afstand a in m
Massieve ligger		2,5–8	$\frac{1}{3}$	–	$\frac{1}{15}$ – $\frac{1}{20}$	–
Gelamineerde ligger		6–25	$\frac{1}{6}$ – $\frac{1}{10}$	$\frac{1}{17}$ – $\frac{1}{20}$	$\frac{1}{20}$	$\frac{\ell}{2}$ $\frac{\ell}{3}$

Figure I.6: Rule of thumb thickness of a glued laminated timber beam [Hofkes et al., 2004, p.180].

I.1.2.3 *Validation modified rule of thumb*

A new rule of thumb of $\frac{h}{l} = \frac{1}{10}$ is applied and checked in MatrixFrame. The new cross sectional are shown in Table I.1.

Cross–sectional Properties	
b	110 mm
h	700 mm

Table I.1: New cross–sectional properties of glulam beam.

ULS: Strength requirement
This results in the stress distribution of Figure I.7. A maximum stress of $18N/mm^2$ is reached, which results in a unity check = 0.71, which is similar to the unity check from the corresponding steel beam of Figure I.2. For this reason, the modified rule of thumb is applied in the parametric model.

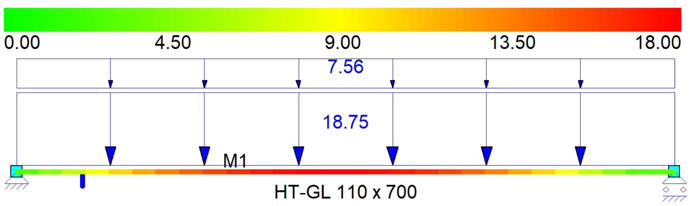


Figure I.7: MatrixFrame result of strength calculation of LC1 with a modified cross-section. Colors reflect the stresses σ_{hh}.

$$u.c. = \frac{\sigma_{hh}}{f_{m,k} \cdot k_{mod}} = \frac{18}{28 \cdot 0.9} = 0.71 \tag{I.5}$$

SLS: Additional deflection requirement
In order to check whether the new cross-section fully passes the requirements, a check on the maximum additional deflection is executed.

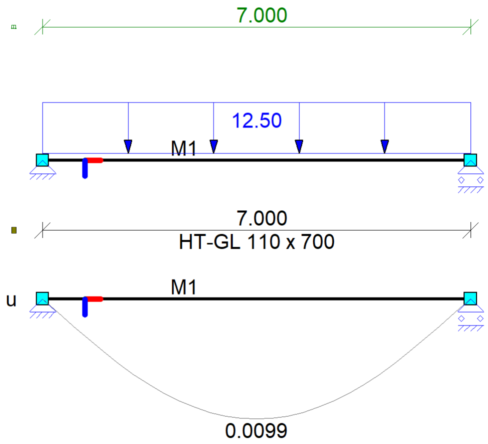


Figure I.8: MatrixFrame result of the additional deflection with a modified cross–section.

$$u_{additional} = 0.0099\ m \tag{I.6}$$

$$u.c. = \frac{u_{additional}}{0.004 \cdot L} = \frac{0.0099}{0.004 \cdot 7} = 0.35 \tag{I.7}$$

The modified cross–section also fulfills the additional deflection requirement.

I.2 VALIDATION OF THE ENVIRONMENTAL IMPACT CALCULATION

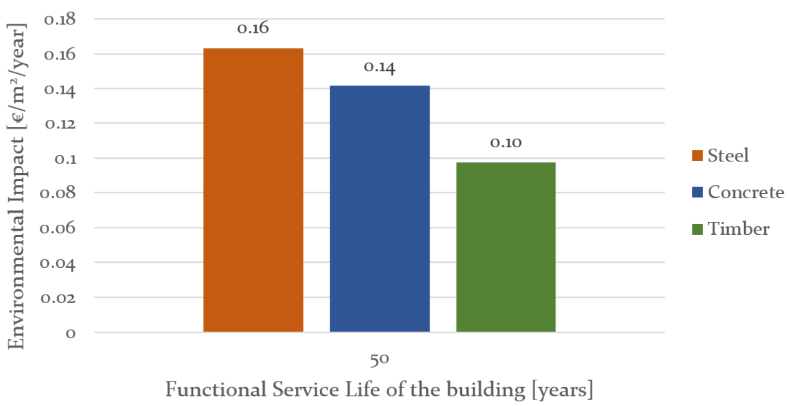


Figure I.9: Environmental impact of the average equation (Scenario 1), which are validated in section 5.2.

I.2.1 Steel design

The environmental impact results of all designs are validated in MPGcalc. The Bill of Materials of the parametric model acts as input for the MPGcalc calculation, see Table I.2

Hollow-core slab	S235 Steel
225120 kg	28711 kg

Table I.2: Bill of Materials steel case-study.

I.2.1.1 *Input MPGcalc*

The Bill of Materials is entered in MPGcalc for each material separately. The framework is separated from the floors, such that the results can be compared, see Figure I.10 and I.11.

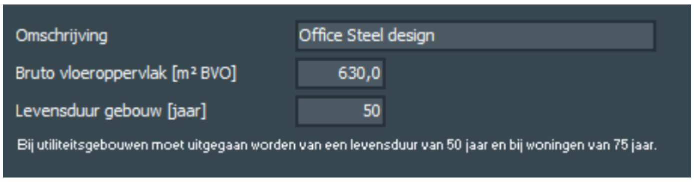
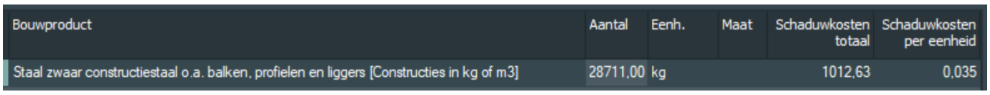


Figure I.10: General MPGcalc input for the project.



(a) MPGcalc input of the structural system (beams, columns and purlins).

(b) MPGcalc input of the floors.

Figure I.11: MPGcalc input of the steel design.

I.2.1.2 *Comparison results*

Results of the comparison are shown in Figure 5.3 and discussed in subsection 5.2.2.

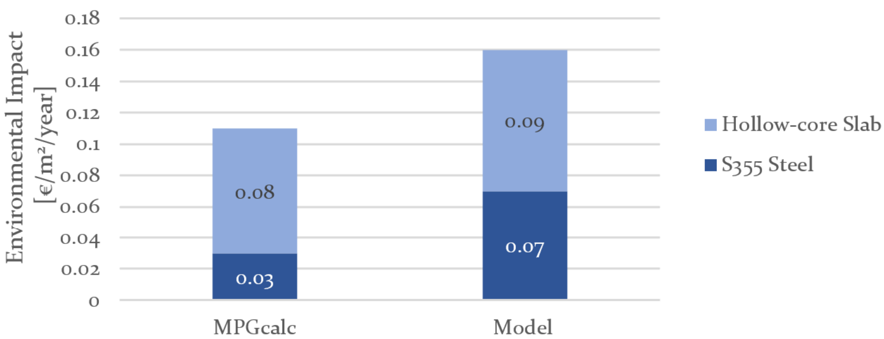


Figure I.12: Comparison of the MPGcalc vs. Developed model environmental impact of the steel design.

I.2.2 Concrete design

The concrete design Bill of Materials is entered similarly as the steel design. The VBI hollow–core slabs are identical. Only the framework differs, as this input is shown in Figure I.13.

	Hollow-core slab	Beams	Purlins	Columns
Amount	450240 kg	189 m	120 m	108 m
Dimensions bxh [mm]	—	350x700	170x330	150x150

Table I.3: Bill of Materials concrete case-study.

I.2.2.1 *Input MPGcalc*

Bouwproduct	Aantal	Eenh.	Maat	Schaduwkosten totaal	Schaduwkosten per eenheid
Betonhuis; beton,in het werk gestort,C30/37,CEMIII; incl.wapening	189,00	m	350×700 mm	1112,87	5,888
Betonhuis; beton,in het werk gestort,C30/37,CEMIII; incl.wapening	120,00	m	170×330 mm	160,85	1,340
Betonhuis; beton,in het werk gestort,C30/37,CEMIII; incl.wapening	108,00	m	150×150 mm	56,87	0,527

Figure I.13: MPGcalc input of the structural system (beams, columns and purlins).

I.2.2.2 *Comparison results*

Results of the comparison are shown in Figure I.14 and discussed in subsection 5.2.3.

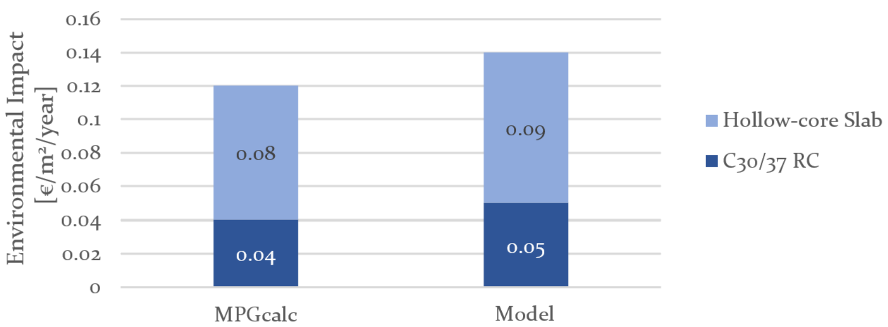


Figure I.14: Comparison of the MPGcalc vs. Developed model environmental impact of the concrete design.

I.2.3 Timber design

I.2.3.1 *Bill of Materials parametric model*

The Bill of Materials resulting from the timber design is summarized in Table I.4. It is remarkable that the Kerto–Ripa flooring is over 20 times lower than its concrete counterpart.

Kerto Ripa floor	Beams	Purlins	Columns	Insulation	Gypsum
24500 kg	7408 kg	600 kg	746 kg	1050 m^2	2100 m^2

Table I.4: Bill of Materials timber case-study.

I.2.3.2 *Input MPGcalc*

For the input in MPGcalc, the glued laminated timber parts are separated from the insulation and gypsum. The reason this insulation and gypsum is necessary is due to the equivalent functional unit of the different designs. As the steel and concrete designs have different concrete floors which already meet sound proofing requirements, the Metsawood Kerto–Ripa floors do not. Therefore, they need the measures as stated above.

Bouwproduct	Aantal	Eenh.	Maat	Schaduwkosten totaal	Schaduwkosten per eenheid
Gelamineerd naaldhout voor constructieve toepassing, duurzaam geproduceerd [Liggers + balken]	189,00	m	117×700 mm	209,95	1,111
Gelamineerd naaldhout voor constructieve toepassing, duurzaam geproduceerd [Liggers + balken]	120,00	m	40×250 mm	19,04	0,159
Gelamineerd naaldhout voor constructieve toepassing, duurzaam geproduceerd [Liggers + balken]	108,00	m	120×120 mm	17,14	0,159
Gelamineerd naaldhout voor constructieve toepassingen, duurzame bosbouw [Constructies in kg of m3]	24500,00	kg		4480,90	0,183

(a) MPGcalc input of the structural system (beams, columns, purlins and Kerto Ripa floors.

Bouwproduct	Aantal	Eenh.	Maat	Schaduwkosten totaal	Schaduwkosten per eenheid
ROCKWOOL RockFit Mono [Isolatielagen]	630,00	m²		465,15	0,738

(b) MPGcalc input of the Rockwool floor insulation.

Bouwproduct	Aantal	Eenh.	Maat	Schaduwkosten totaal	Schaduwkosten per eenheid
Akoestisch gipskartonplafond, enkel geperforeerde plaat met isolatie (NBVG) [Verlaagde plafonds]	630,00	m²		845,04	1,341

(c) MPGcalc input of the gypsum sound absorbant boarding.

Figure I.15: MPGcalc input of the timber design.

I.2.3.3 *Comparison results*

Results of the comparison are shown in Figure I.16 and discussed in subsection 5.2.4.

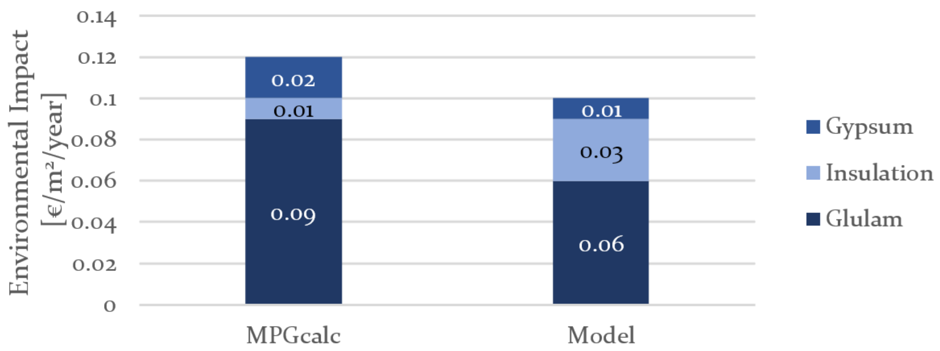


Figure I.16: Comparison of the MPGcalc vs. Developed model environmental impact of the timber design.

Straightening the impact of glued laminated timber
a modification due to the big difference in environmental impact for the glued laminated timber can be made. In the Developed model, the environmental impact of the timber is multiplied with a factor of 1.5. This results in a similar impact as MPGcalc. Standard, the original model is used, but when the modified timber results are used, this is marked with a "B", as shown in Figure I.17.

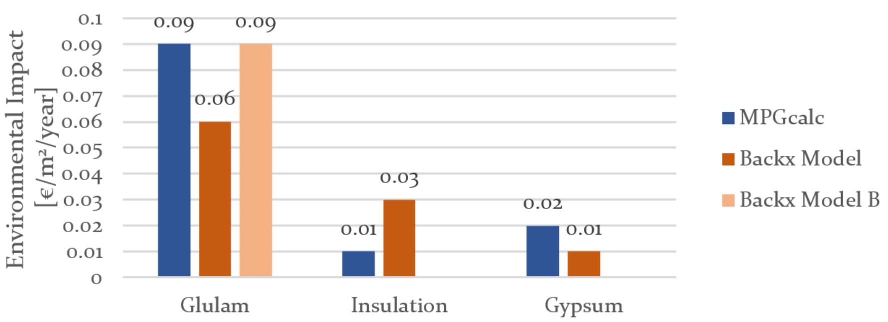


Figure I.17: Comparison of the MPGcalc vs. Developed model vs. Developed model B environmental impact of the timber design.

J SENSITIVITY ANALYSIS

J.1 CHOSEN PARAMETERS TO RESEARCH

Steel Design						
	S355			Hollow–core slab		
Parameter	**-10%**	**Basis**	**+10%**	**-10%**	**Basis**	**+10%**
BCI	0.684	0.76	0.836	0.189	0.21	0.231
P_{R4}	0.675	0.75	0.825	0.18	0.20	0.22
P_{R5}	0.675	0.75	0.825	0.18	0.20	0.22
TSL	135	150	165	135	150	165
Concrete Design						
	RC C30/37			Hollow–core slab		
Parameter	**-10%**	**Basis**	**+10%**	**-10%**	**Basis**	**+10%**
BCI	0.189	0.21	0.231	0.189	0.21	0.231
P_{R4}	0.18	0.2	0.22	0.18	0.2	0.22
P_{R5}	0.18	0.2	0.22	0.18	0.2	0.22
TSL	135	150	165	135	150	165
Timber Design						
	Glulam			Insulation + Gypsum		
Parameter	**-10%**	**Basis**	**+10%**	**-10%**	**Basis**	**+10%**
BCI	0.54	0.6	0.66	-	-	-
P_{R4}	0.45	0.5	0.55	-	-	-
P_{R5}	0.45	0.5	0.55	-	-	-
R_3	0.72	0.8	0.88	-	-	-
TSL	67.5	75	82.5	36	40	44

Table J.1: Parameters as researched in the sensitivity analysis. The results are based on scenario 4, which includes both the use of a donor framework and remountability.

J.2 OUTPUT

Steel Design		-10%	Basis	10%
S235	BCI	1.87	0	-1.87
	P_r4	2.736236	0	-2.73715
	P_r5	1.871197	0	-1.87211
	TSL	1.985742	0	-1.6247
Hollow-Core Slab	BCI	0.204347	0	-1.26274
	P_r4	0.81464	0	-0.20526
	P_r5	0.1961	0	-0.1961
	TSL	0.126457	0	-0.10446

(a) Output of the steel reference design.

Concrete Design		-10%	Basis	10%
RC	BCI	0.08	0	-0.08
	P_r4	0.34	0	-0.34
	P_r5	0.08	0	-0.08
	TSL	0.06	0	-0.05
Hollow-Core Slab	BCI	0.17	0	-0.17
	P_r4	0.70	0	-0.70
	P_r5	0.17	0	-0.17
	TSL	0.11	0	-0.09

(b) Output of the concrete reference design.

Timber Design		-10%	Basis	10%
Glulam	BCI	-0.80	0	0.80
	P_r4	2.79	0	-2.79
	P_r5	-0.80	0	0.80
	R3	3.13	0	-3.13
	TSL	1.53	0	-1.25
Insulation	TSL	0.00	0	0.00

(c) Output of the timber reference design.

Figure J.1: Output of the sensitivity analysis from the different reference designs, calculated with scenario 4 from subsection 4.4.2.