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# The potential benefit of industrial construction in $CO_2$ savings

A comparison with traditional construction and possibilities to reduce the environmental impact of industrial construction


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## Preface

Dear reader,

In front of you is the master's thesis "*The potential benefit of industrial construction in $CO_2$ savings - A comparison with traditional construction and possibilities to reduce the environmental impact of industrial construction*". This thesis was written to fulfil the graduation requirements of the master's Programme in Sustainable Energy Systems Management at EUREC and was commissioned by Copper8. I researched and wrote this thesis from August 2023 to March 2024.

After taking a gap year to travel to Southeast Asia and completing a bachelor's degree in Built Environment, I have decided to pursue a Master's degree. My motivation for doing so is to work on projects where I can make a positive impact on the world and challenge myself. This master's program not only offers interesting subject matter and challenging assignments but also provides personal growth opportunities. For example, for my specialisation in Sustainable Energy Management, I moved from Groningen to Zaragoza and then to Amsterdam for this thesis.

Special thanks go out to my supervisors from Copper8, Sybren Bosch and Stefan Favrin, for their advice and guidance during the internship at Copper8. Moreover, special thanks to all the colleagues from Copper8 for their advice. Also special thanks to my fellow students from Hanze University of Applied Sciences and the University of Zaragoza for their listening ears and sharing their journey. Lastly, special thanks go out to my supervisor, Frank Pierie, for his guidance and advice.

With kind regards,

Hanna

Amsterdam, 4th of March, 2024

## Abstract

The housing sector in the Netherlands needs to reduce its environmental impact while building 100,000 houses a year. As industrial construction is faster and cheaper, it is seen as one of the solutions for those challenges. There is also a perception that industrial construction is more sustainable. However, to the authors' knowledge, this has not been quantitatively researched anywhere. The environmental impact of houses is currently quantified by the MPG (Environmental Performance of Buildings) but construction firms face difficulties calculating the exact environmental impact using this. Therefore, it is currently not possible to compare the construction methods based on the MPG.

This study aims to quantify the potential benefit of industrial construction compared to traditional construction by comparing the currently insufficiently reflected topics in the MPG calculation. For this purpose, the following main question was formulated: "*What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction when focussing on the currently insufficiently reflected topics in the Production and Construction phase of the MPG calculation?*".

First, a literature review and semi-structured interviews were conducted to identify the currently insufficient reflected differences between the construction methods in the MPG calculation. After that, overviews and models were created to visualise and quantify and compare those differences (based on three different case studies). These comparisons aim to determine the potential benefit of industrial construction in $CO_2$ savings. Assumptions were mainly based on interviews and literature when available. Finally, a literature review and semi-structured interviews resulted in recommendations for key stakeholders in reducing the environmental impact of industrial construction.

This study focuses solely on the Production and Construction phase of the MPG calculation. Due to limited data availability, certain assumptions were made during the model creation process. Recommendations for stakeholders are based on interviews with a limited number of participants due to time constraints. Different results may be obtained with a different scope, other assumptions or other interviewees.

Results of interviews indicate that the currently insufficiently reflected topics are established in the Construction Phase. The topics that need more precise calculations, to make a fair comparison between the construction methods, are transport and machinery, construction waste and the construction of the housing factory.

Results show that 25-49% (depending on the construction methods of the scenarios) of $CO_2$ emissions could be saved per $m^2$ gross floor area by opting for industrial construction instead of traditional construction. The differences between traditional and 3D industrial construction are greater than the differences between hybrid and 2D industrial construction.

To reduce the environmental impact of industrial construction, recommendations include enforcing stricter regulations for sustainable construction, monitoring the MPG regulations, improving communication, providing Category-1 data, exploring alternatives to diesel trucks and investing in sustainable materials.

## Table of content

## List of abbreviations

| | |
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| Bvo | Bruto Vloer Oppervlak ($m^2$) |
| | Gross Floor Area ($m^2$) |
| BCI | Building Circularity Index (between 0.00 (linear) – 1.00 (circular) |
| C&D | Construction and demolition waste |
| EPD | Environmental Product Declaration, based on LCA |
| GWP-100 | Global Warming Potential over 100 years ($kgCO_2$) |
| HSB | Hout Skelet Bouw |
| | Timber Frame Construction |
| LCA | Life Cycle Analysis |
| MKI | Milieu Kosten Indicator |
| | Environmental Costs Indicator |
| Module A | Production and construction phase of the MPG calculation |
| MPG | Milieu Prestatie Gebouwen (€/$m^2$bvo jaarlijks) |
| | Environmental Performance of Buildings (€/$m^2$bvo annually) |
| MPG-2 | Studies the $CO_2$ emissions emitted in Module A |
| NMD | Nationale Milieu Database |
| | National Environmental Database |
| NZEB | Nearly Zero Energy Building |
| OSB | Oriented Strand Board |

## 1. Introduction

The housing construction industry within the Netherlands is currently encountering significant obstacles. Primarily, the Netherlands is striving to expedite housing construction, targeting an annual output of 100,000 houses [1]. Simultaneously, the government has established objectives to decrease GHG emissions by 55% by 2030, to be climate-neutral in 2050 [2] and to develop a complete circular economy in 2050 [3].

To achieve the necessary growth in housing production while maintaining sustainability, industrial construction is acknowledged as one of the solutions by the Dutch government [4]. Within this context, the Dutch government aims to achieve a goal of manufacturing 50% of all new houses using industrial construction by 2030 [4].

> *Traditional construction* takes place on the construction site and construction materials are transported from suppliers to the construction site [15]. *Industrial construction* (2D or 3D) takes place in the factory. Elements are made here and transported to the construction site, where the elements are assembled [19]. *Hybrid construction* is a combination of traditional and industrial construction. In this study, hybrid construction is considered traditional.

Research shows that industrial construction increases production efficiency, shortens construction duration [4, 5], decreases labour demand and reduces maintenance expenses [5]. The perception is also that industrial construction of houses could decrease the environmental impact in the construction industry [4]. However, to the authors' knowledge, this has not been quantitatively researched anywhere.

Even if industrial construction results in a decreased environmental impact compared to traditional construction, the environmental impact must be reduced to reach the aforementioned objectives. I.e., the construction sector was responsible for 11% - for only the construction processes - of all emissions in the Netherlands in 2021 [8].

In the construction sector within the Netherlands, the environmental impact is currently quantified by the MPG (Environmental Performance of Buildings). The MPG takes into account the environmental impact of the materials used in a building, expressed in euros per square meter gross floor area annually (€/m$^2$bvo annual) [6].

> The MPG calculation consists of four modules: A, B, C and D. *Module A* calculates the impact of the Production (A1- A3) and Construction (A4-A5) phase. *Module B* (B1-B7) calculates the impact of the Use phase. *Module C* (C1-C4) calculates the impact of the Demolition and Processing phase and *Module D* calculates the impact of reuse and recycling opportunities [18].

In essence, the MPG indicates the cost required to compensate for the environmental impact of construction. The MPG calculation could be used to compare the environmental impact – and consequently cost – between the traditional and industrial construction methods. However, the hypothesis is that the MPG calculation is currently not developed enough to accurately calculate the environmental impact of industrially constructed houses [7].

The reason for the perception that the MPG calculation is currently not accurate enough to compare traditional and industrial construction is that it is expected that certain key components with an environmental impact are currently not included. This could be the reason why the MPG does not differentiate between the environmental impact of traditional and industrially built houses [7].

## 1.1 Gap in knowledge

Although theoretically, the MPG can be used to determine the difference between the environmental impact of traditional and industrial construction, the reality is that construction firms face various challenges in accurately calculating the MPG of their constructed houses. The most important of these challenges is the lack of data on various fronts. Therefore it is not possible to make a fair comparison between the construction methods and thus to determine the potential benefit of industrial construction. Two of those data gaps are addressed in this thesis, namely:

- Certain components that affect the environmental impact are currently not addressed or not properly documented in the MPG calculation. Either assumptions are made or the missing data is left out of the analysis [7];
- At the moment, the MPG score of both construction methods (when using the same materials) would be the same [7]. It is therefore not possible to compare the environmental impact of traditional and industrial construction with the current MPG calculation, nor to say anything about the potential environmental benefits of industrial construction.

## 1.2 Research aim and questions

The first objective of this study is to identify the differences between the environmental impact of traditional and industrial construction that are currently perceived to be insufficiently reflected in the MPG calculation. Based on these results, the aim is to provide an adapted MPG calculation that includes those differences that are needed to accurately calculate the environmental impact of the construction methods. This part of the study is called the preliminary research. Results will be used to answer the main question of this study. The main question is based on the second objective.

The second objective is to make a fair comparison between traditional and industrial construction to find out what the potential environmental benefit of industrial construction is in $CO_2$ savings. This will be done by quantifying the insufficiently reflected differences with the adapted MPG calculation based on three case studies. It is important to research what the potential environmental benefit of industrial construction is compared to traditional construction since it is considered a potential solution to the current housing problem in the Netherlands [4].

This second objective results in the following main question of this study:

> *What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction when focusing on the currently insufficiently reflected topics in the Production and Construction phase of the MPG calculation?*

Results (Chapter 4) indicate that the currently insufficiently reflected topics, that do result in differences in environmental impact between traditional and industrial construction in the Production and Construction Phase of the MPG calculation, are the impact of transport and machinery (+), construction waste (+) and the construction of the housing factory (-). As this study examines the potential benefits of industrial construction in terms of $CO_2$ savings, a plus (+) indicates an expected positive effect for industrial construction and a minus (-) indicates an expected negative effect for industrial construction.

Those aforementioned differences are being quantified with the help of the following sub-questions. Those sub-questions aid in comparing the construction methods and finally determine the potential benefit of industrial construction.

1. What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction in terms of transport and machinery within the Construction phase of the MPG calculation?
2. What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction in terms of construction waste within the Construction phase of the MPG calculation?
3. What is the environmental impact (in $kgCO_2$) of constructing the housing factory needed for hybrid and industrial construction?
4. When comparing the calculated impact of the aforementioned sub-questions, what is the potential environmental benefit of industrial construction?

As the construction sector is still responsible for a significant proportion of $CO_2$ emissions, the third objective is to provide recommendations for stakeholders to reduce the environmental impact of industrial construction.

### 1.3 Reading guide

This section visualises and describes the setup of the master's thesis. Chapter 2 describes the background information about the current MPG calculation. This is followed by Chapter 3 describing the system boundaries for the different Phases, the research approach and the methodologies.

Chapter 4 presents the results of the preliminary research (the issues with the MPG calculation, the currently insufficiently reflected topics in the MPG and the adapted MPG calculation as used in this study). Chapter 5 shows the cases and scenarios and Chapter 6 describes the creation and validation of the models.

Chapter 7 and Chapter 8 give the results of the sub-questions. First, the overviews of transport and machinery and construction waste in the Construction Phase of the MGP calculation as a result of the conducted interviews are presented. Secondly, the potential environmental benefit in $CO_2$ savings of industrial construction compared to traditional construction is presented.

Chapter 9 describes the discussion and limitations, followed by Chapter 10 giving the conclusion.

Chapter 11 gives recommendations for key stakeholders in reducing the environmental impact of industrial construction. After that, Chapter 12 describes options for further research and finally, Chapter 13 gives an overview of the references.

## 2. Background information on MPG calculation

This chapter aims to elaborate on the current MPG calculation used in the construction sector to determine the environmental impact of constructed houses. The MPG is expressed in euros per square meter gross floor area annually (€/m$^2$bvo annually) and indicates the cost required to compensate for the environmental impact [8].

Based on the EN 15804 method, Life Cycle Analyses (LCAs) for construction products are determined. Those LCAs result in the environmental impact of different (11+) topics, for example, human toxicity, acidification or climate change (GWP-100), called Environmental Impact Factors [9].

For every Environmental Impact Factor, a shadow cost was determined. Those shadow costs result in an MKI (Environmental Costs Indicator) in €/m$^2$ for a certain construction product [9]. The National Environmental Database (NMD) collects those MKIs in the so-called Environmental Profiles.

Adding those MKIs for all the construction products used in a house divided by the expected lifetime and the gross floor area (bvo) of the house results in the final MPG score (Figure 1) in €/m$^2$bvo annual [9]. The lower the MPG score, the lower the environmental impact [9].

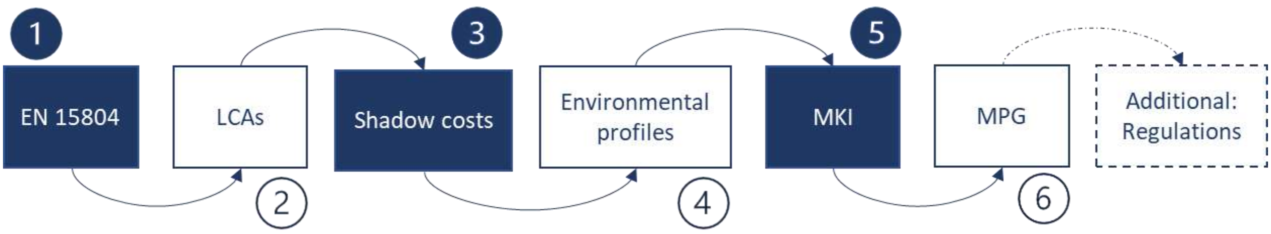


*Figure 1 Overview of the roadmap that leads eventually to the MPG score*

**Step 1: EN 15804**

The EN 15804 is a standardised European norm that specifies how an LCA of a product should be carried out. It describes the different life cycles of a (in this case: construction) product. Those different life cycles are divided into Modules A-D:

A. The Production and Construction Phase (+);
B. The Use Phase (+);
C. The End of Life Phase (+);
D. Possibilities for re-use (-).

The results of each Module (despite Module D) increase the MPG score. Module D describes the possibilities for re-use and therefore could lower the final MPG score. Each Module consists of different sub-modules, as presented in Figure 2 [8].

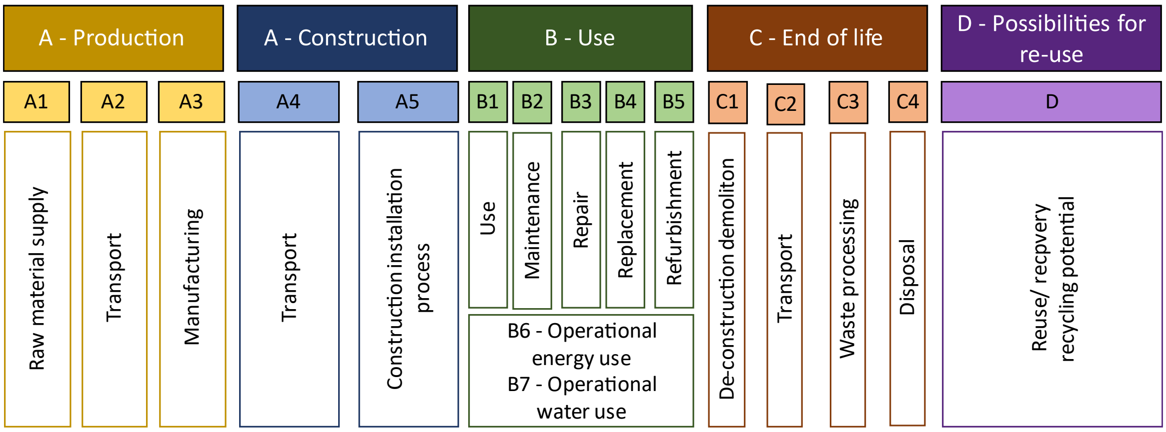


*Figure 2 The life cycles of a product according to EN 15804*

### Step 2: LCAs

An LCA is conducted to determine the environmental impact of a construction product based on the modules from EN 15804. To calculate the environmental impact, multiple environmental impact factors are used. Starting in January 2021, the number of environmental impact factors has increased from 11 to 19 [9]. Examples of environmental impact factors are human toxicity, climate change (GWP-100), ozone layer depletion or acidification [9]. Those impact factors are used for determining the environmental impact of the life cycle of a construction product [10].

### Step 3: Shadow costs

To convert environmental impact factors to costs, a price was calculated per environmental impact factor. These so-called shadow costs are based on the amount of 1,4-dichlorobenzene equivalents (1,4-DCB eq.) and the effect of 1,4-DCB eq. on certain environmental impact factors [10]. With these shadow costs, the environmental impact of the lifecycle of a construction product can be expressed in euros. All this information is described in the so-called Environmental Profile of a construction product.

### Step 4: Environmental Profiles

The National Environmental Database (NMD) collects these Environmental Profiles. Unfortunately, it is not feasible to conduct an LCA for every construction product due to the high cost and time required [7]. Additionally, many construction products share similarities, making it unnecessary to conduct an LCA for every product [7]. As a result, there are three categories of Environmental Profiles, presented in Figure 3 from most to least accurate [8].

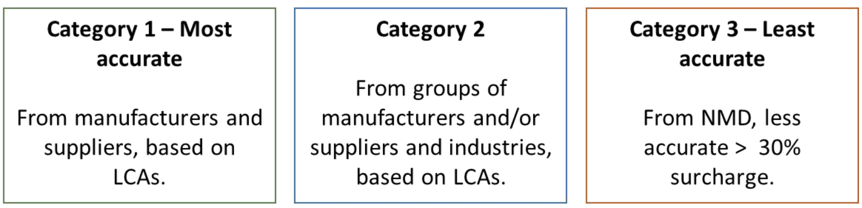


*Figure 3 Categories for Environmental Profiles according to the NMD*

**Step 4: MKI**

The MKI (Environmental Costs Indicator) is presented in the Environmental Profile of the construction product. The MKI presents the environmental impact of a certain product during the lifetime of one unit product in €/m$^2$ (e.g. 1 m$^2$ of façade cladding) [9].

**Step 5: MPG**

The MKI can be converted to the MPG by calculating the total impact of all the construction products used in a house back to a functional unit (€/m$^2$bvo annual). For example, when a house has an expected lifecycle of 75 years, a frame with an expected life cycle of 25 years has to be replaced two times after assembling the frame in the Construction Phase.

$$MPG = \frac{MKI \cdot A \cdot x}{expected\ lifetime \cdot bvo}$$

The final MPG is calculated by the previously presented formula, where:

- The MPG is expressed in €/m$^2$bvo annual;
- The MKI is expressed in €/m$^2$ considering the lifetime of a product;
- A is expressed in m$^2$, describing the amount of the certain construction product used in a house;
- x has no unit and describes the number of times the certain construction product has to be replaced during the expected lifetime of the constructed house;
- The expected lifetime of the constructed house is expressed in years;
- The bvo is the gross floor area of the constructed house, expressed in m$^2$.

**Additional: Regulations**

Every newly constructed house must provide an MPG calculation to obtain permission from the local government to construct the house and the MPG score must meet the current requirements [6]. Since January 2021, the maximum limit for the MPG was 0.8 €/m$^2$bvo annually [6]. The aim is to gradually tighten the requirement and halve it by 2030 at the latest [6].

However, the expansion of environmental impact factors has the effect of including more environmental impacts in the MPG score, resulting in a higher MPG [11]. The MPG target remains the same, but instead of reaching 0.5 €/m$^2$bvo annually as planned, it will now be 1.0 €/m$^2$bvo annually [11].

# 3. Methodology

This section aims to describe the research phases (3.1), the system boundaries (3.2), the research approach (3.3) and the methods (3.4) as conducted in this study.

## 3.1 Research phases

The study is divided into three research phases. A different system boundary was used for each research phase.

- **Phase I** (preliminary research): Identifying the differences between traditional and industrial construction that are currently perceived to be insufficiently reflected in the MPG and establishing an adapted MPG calculation that includes those insufficiently reflected differences. Results of Phase I are presented in Chapter 4;
- **Phase II** (main question): Quantifying the currently insufficiently reflected differences identified in Phase I based on the adapted MPG calculation created in Phase I and determining the potential benefit of industrial construction in $CO_2$ savings. Results of Phase II are presented in Chapter 7;
- **Phase III** (recommendations): Providing recommendations for key stakeholders in reducing the environmental impact of industrial construction. Results of Phase III are presented in Chapter 11.

## 3.2 System Boundaries

This study solely focuses on the Production and Construction Phase (also: Module A) of the MPG calculation, because the peak in emissions occurs within the first four years. Those first four years are crucial for the environmental impact and demonstrated in Module A [7]. Additionally, the most significant knowledge gap can be found here since construction firms often do not exactly know what happens here, particularly in the Construction Phase (Modules A4-A5) [7].

The various phases employed different system boundaries. Figure 4 zooms in on the Production and Construction Phase of the MPG calculation and describes Modules A1 – A5 in words. As mentioned before, this adapted MPG calculation is a result of Phase I and will be elaborated in Chapter 4.2. It is presented here to provide an understanding of the system boundaries of this study.

The system boundary for Phase I is limited to the Production and Construction Phase (Module A) of traditional and industrial construction. This phase outlines the preliminary research of the study and results in a list of currently insufficiently reflected topics in the MPG calculation and an adapted MPG calculation that will be further used in this study to determine the potential environmental benefit of industrial construction compared to traditional construction.

Subsequently, the system boundary for Phase II is limited to the Construction Phase of the adapted MPG calculation (also: Modules A4-A5) of traditional and industrial construction. This is because the identified differences from Phase I are located in these modules. Instead of calculating all environmental impact factors of the MPG calculation, the focus will be solely on the $CO_2$ emissions due to time constraints.

Finally, the system boundary for Phase III is limited to the Production and Construction Phase (Module A) of purely industrial construction, to provide stakeholders with recommendations for reducing their environmental impact.

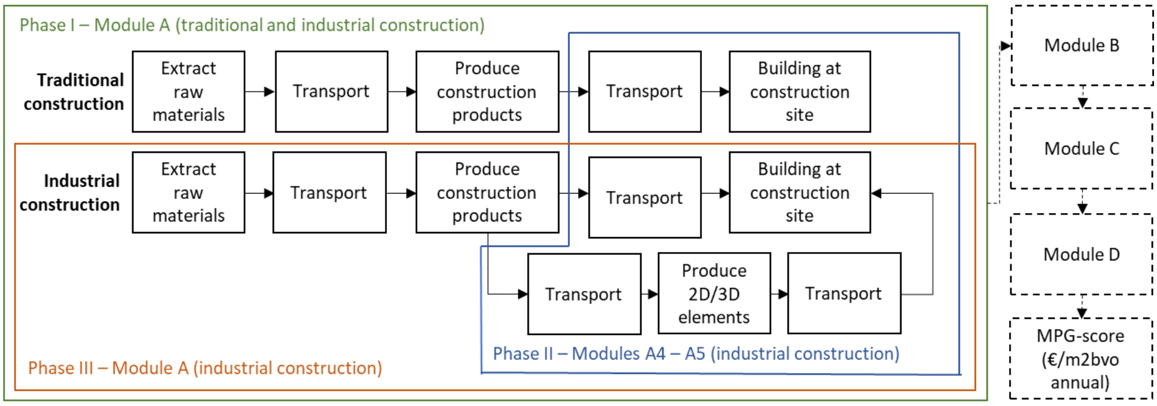


*Figure 4 System boundaries Phase I, II and III of this study*

### 3.3 Research approach

The purpose of this section is to describe the research approach of the three phases previously described. The methods conducted in the different phases are further explained in Chapter 3.4.

The research approach of Phase I (Figure 5) starts with desk research on the MPG calculation, traditional and industrial construction. Based on the data collected, questions for the semi-structured interviews were devised. These interviews aimed to identify the differences between the construction methods that are currently perceived to be insufficiently reflected in the MPG calculation.

These interviews also aimed to collect other issues that construction firms have with the current MPG calculation. These resulted in an adapted MPG calculation that could be used to compare the environmental impact of the construction methods and finally, to determine the potential benefit of $CO_2$ savings for industrial construction. The results of Phase I are presented in Chapter 4.

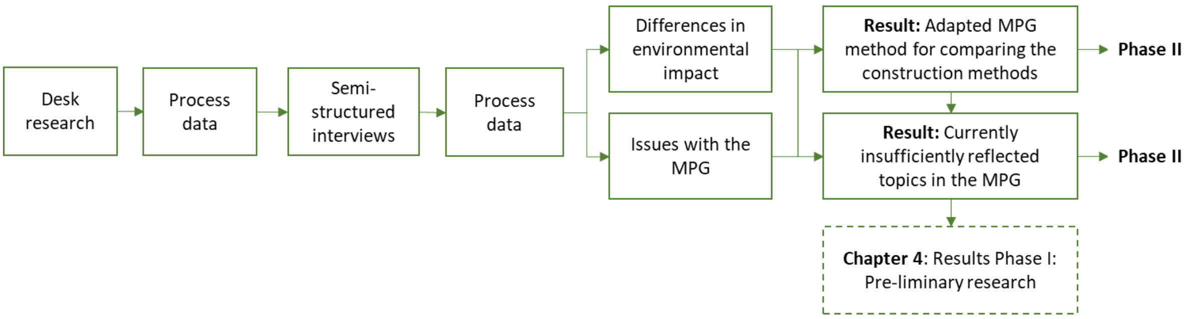


*Figure 5 Research approach Phase I*

The research approach of Phase II (Figure 6) builds on the identified differences and uses the adapted MPG calculation (results from Phase I) to determine the potential benefit of industrial construction in $CO_2$ savings. Therefore, three case studies (Chapter 5), each consisting of two comparable scenarios were used to make a comparison between traditional and industrial construction.

To determine the potential benefit of industrial construction (in $CO_2$), different models (Chapter 6) were created in Excel to compare traditional and industrial construction on the topics of transport and machinery, construction waste and the construction of the housing factory. The results of Phase II are presented in Chapters 7 and 8.

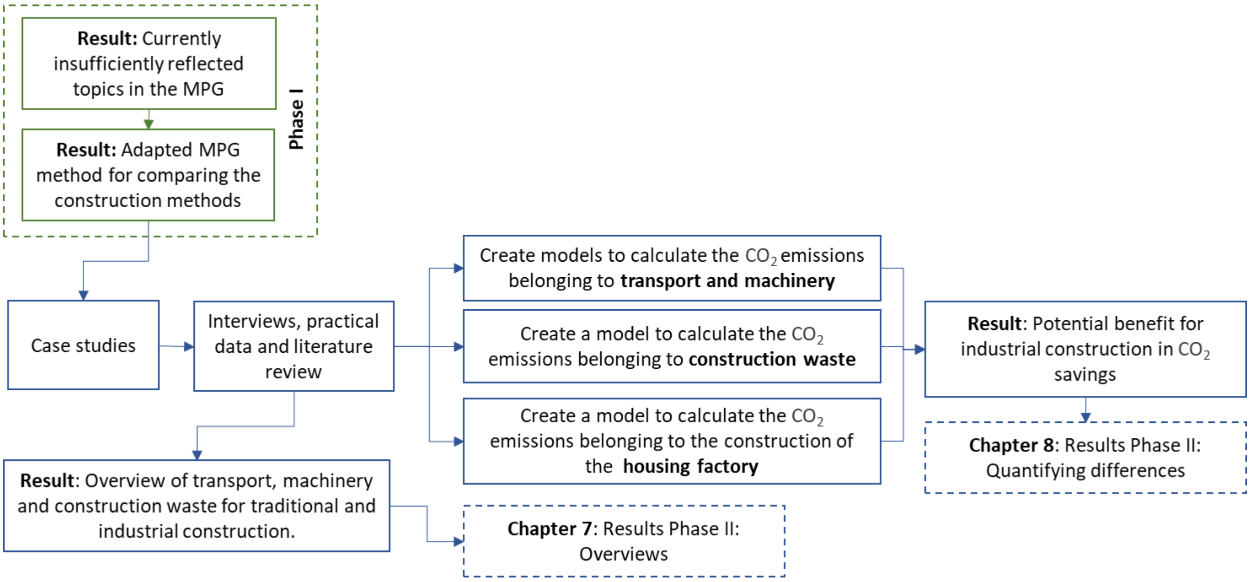


*Figure 6 Research approach Phase II*

The research approach of Phase III (Figure 7) starts with desk research into the environmental impact of industrial construction. There was limited scientific data available, which is why semi-structured interviews with different stakeholders in industrial construction were conducted. These interviews aimed to identify the opportunities and barriers to reducing the environmental impact of industrial construction. Based on these results, recommendations for those key stakeholders were conceived. The results of this phase are presented in Chapter 11.

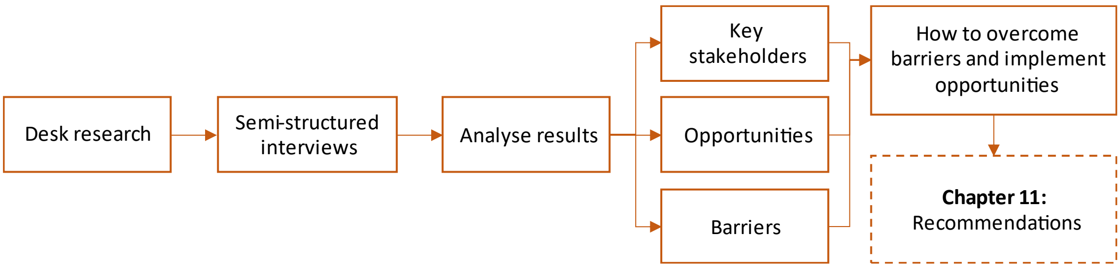


*Figure 7 Research approach Phase III*

### 3.4 Research methods

This section describes the methodologies that were used to answer the main question. This study is a combination of quantitative and qualitative research. In particular, Phases I and III involve qualitative research, while Phase II is a quantitative study. The following methods are used in this study.

**Desk research:** desk research was conducted mainly to identify the data gap. It also served as the foundation for the interview questions and provided input for the models.

**MPG:** the MPG calculation (Chapter 2) has been used as a basis for comparison between traditional and industrial constructed houses. This research focuses on calculating the impact of certain activities conducted in the Production and Construction Phase of the MPG calculation.

**LCA:** the MPG uses the Life Cycle Analysis approach to calculate the environmental impact of a construction product (Chapter 2). This study uses a small part of the LCA approach to calculate the $CO_2$ emissions associated with the currently insufficiently reflected identified differences.

**Creating flowcharts:** based on the results of desk research and interviews, flowcharts were created to provide an overview of transport and machinery and construction waste in traditional and industrial construction. Those overviews aim to visualise the differences between the construction methods.

**Creating models:** different models were created in Excel to calculate the $CO_2$ emissions belonging to the currently insufficiently reflected identified differences between traditional and industrial construction.

It is important to note that the models are created to calculate the $CO_2$ emissions belonging to the case studies used in this research. In other words, there is no universal model created to assess the environmental impact of various construction methods.

**Case studies:** case studies were used to make a comparison between the construction methods in Phase II. Those case studies were delivered by construction firms. Each case study consists of two scenarios. In particular, a traditional or hybrid (in this study also traditional) scenario and a comparable (2D or 3D) industrial scenario.

It is important to note that the scenarios can be compared with each other, but the case studies cannot be compared. In other words, the results of Case A and B cannot be compared, but the results of the scenarios of Case A, the traditional and 3D industrial scenario, can be compared. This is due to different assumptions made during the creation of the models.

**Expressions:** the MPG is expressed in €/$m^2$bvo annually (euro per square meter gross floor area), in this research the results are calculated in kg$CO_2$ or GWP-100 (Global Warming Potential over 100 years [9]). This is one of the (current: 11, in the future: 19) environmental impact factors on which the MPG is determined (see also Chapter 2 for more information about the current MPG calculation) [8].

The models created in this study are used to determine the potential benefit of industrial construction in $CO_2$ savings. This study uses case studies and scenarios and thus results are shown in kg$CO_2$/scenario. The Scenarios from Case C do not have the same gross floor area (bvo), which is why results are also converted to kg$CO_2$/$m^2$. Differences between the environmental impact of the construction methods are expressed in kg$CO_2$/scenario, kg$CO_2$/$m^2$bvo and in percentages.

**Company visits:** several site visits were carried out to gain an understanding of the housing factories. These were often combined with interviews.

**Semi-structured interviews:** Semi-structured interviews were conducted because they allow for comparison of answers while also providing flexibility to deviate from the topic if necessary. During the three phases, the following interviews were conducted:

- Phase I: interviews with sustainability experts of different construction firms (both traditional and industrial) were conducted to identify the differences between construction methods and the issues with the current MPG calculation;
- Phase II: interviews with work planners from construction firms (both traditional and industrial) and transport companies were conducted to elaborate the case studies and make substantiated assumptions for creating the models that calculated the environmental impact;
- Phase III: interviews with sustainability experts of different construction firms were conducted to identify key stakeholders, opportunities and barriers in reducing the environmental impact of industrial construction.

The interviews' results were analysed, categorised and prioritised together with a Copper8 consultant specialised in circular construction. Due to privacy reasons, the names of interviewees are not disclosed in this research paper. All the interviews will be identified as one interviewee in the references and mentioned in the text as: [7]. A list of the roles of these interviewees and what data they provided is attached in Appendix A.

**Validation and verification of the models:** validation and verification of the models are needed to check whether the correct models are built and to check whether the models are built correctly.

The validation process focuses on the goal of the model to find out if the correct model was built. The verification of this model is done by several methods. Those methods are described in the study of Sargent (2013), Verification and validation of simulated models [10]. Verification methods used were: comparing to other models, tracing, extreme condition tests, face validity and using a calculator to check formulas.

# 4. Results Phase I: Pre-liminary research

This section describes the results from Phase I. It starts with the results from the interviews (4.1), the adapted MPG calculation as applied in this research (4.2) and the observations of Phase I (4.3).

## 4.1 Results from interviews

This text presents the issues that construction firms face while calculating the MPG of industrial constructed houses that are relevant to this study. Other mentioned issues with the MPG are described in Appendix C.

**Issues with the current MPG calculation**

The first issue with the Production and Construction Phase of the MPG calculation is that the Construction phase is often empty because it is unclear what happens there [7]. Conversely, the Production Phase is often relatively well calculated. This is because the Production Phase calculates the environmental impact at product level, where it is often known what happens. This is not the case in the Construction Phase [7], which is on project level. Therefore, it could be stated that the currently insufficiently reflected differences lay in the Construction phase of the MPG calculation.

The second issue is that sometimes, industrial-produced houses or houses constructed with sustainable materials[1] result in a higher MPG score compared to their traditional alternatives [7]. The absence of Category-1 data for those construction products is the reason for this. Ideally, the 2D and 3D elements produced in the housing factory, along with sustainable materials, would provide Category-1 data. However, this is not always the case due to financial and time limitations. [7].

Another issue is that for a house constructed traditionally and industrially, with similar materials, the MPG score will be the same [7]. This is not realistic as the construction methods do not have the same environmental impact. This is among others due to the lack of calculation of several topics that do lead to differences in the environmental impact of the construction methods.

**Differences between the construction methods that are perceived to be insufficiently reflected in the current MPG calculation**

The fact that no differences are visible in MPG scores for traditional and industrial construction may be due to not calculating the environmental impact of the following topics.

The first topic that needs more accurate calculations to make a fair comparison between the construction methods is transport and machinery. Industrial construction is expected to involve fewer logistical movements, among others due to more efficient transport. This should lead to a reduction in environmental impact for industrial construction. However, this is currently not included in the MPG calculation. The hypothesis is that calculating

[1] Sustainable materials are materials with a reduced environmental impact compared to their traditional alternative (e.g. biobased or secondary materials).

the environmental impact of transport and machinery for the case studies results in a positive (+) difference in favour of industrial construction.

Secondly, the impact of construction waste is not taken into account at all, while this is where major differences arise between construction methods [7]. This is due to the MPG being calculated based on technical drawings and not on the materials ordered and used to construct a house [7]. Industrial construction is expected to generate less construction waste. This is due to better optimisation of construction waste in the factory compared to the construction site. The hypothesis is that calculating the environmental impact of construction waste for the case studies results in a positive (+) difference in favour of industrial construction.

Finally, the impact of the construction of the housing factory needed for industrial and hybrid construction is not included in the current MPG calculation [7]. A possible reason is that the environmental impact of the housing factory not directly influences the environmental impact of the constructed houses. However, this study is about making a fair comparison between the construction methods and constructing a housing factory has a major impact on the environment. The hypothesis is that calculating the environmental impact of the construction of a housing factory results in a negative (-) difference for industrial construction.

To summarize, the differences that are currently perceived to be insufficiently reflected in the MPG, and thus further used in this study to determine the potential benefit of industrial construction compared to traditional construction, are:

- The impact of transport and machinery (+);
- The impact of construction waste (+);
- The impact of the construction of the housing factory (-).

## 4.2 Adapted MPG calculation

Based on the aforementioned issues, an adapted MPG calculation was established. This adapted calculation aims to include the currently insufficiently reflected differences between traditional and industrial construction in the MPG calculation that are needed to determine the potential benefit of industrial construction compared to traditional construction.

Figure 8 provides the overview of the Production and Construction Phase of the MPG calculation according to the NMD (a detailed version of the current MPG calculation is described in Chapter 2) and adapted to distinguish the environmental impact of traditional and industrial construction.

According to the NMD, and thus the original MPG calculation, the Production and Construction Phase consists of five modules. However, based on results from Phase I, the following steps are added or distinguished:

- A1 Extracting raw materials needed for the house;
- A2 Transport of raw materials to suppliers;

- A3.1 Produce construction products;
- A4.1 Transport of construction products directly to the construction site;
- A4.2* Transport of construction products to industrial construction firm;
- A3.2* Produce 2D- or 3D elements in the factory;
- A4.3* Transport of 2D- or 3D elements from factory to the construction site.
- A5 Construct the house on the construction site.

*These steps are distinguished in this study and are normally not mentioned in the official MPG calculation as presented in Chapter 2.*

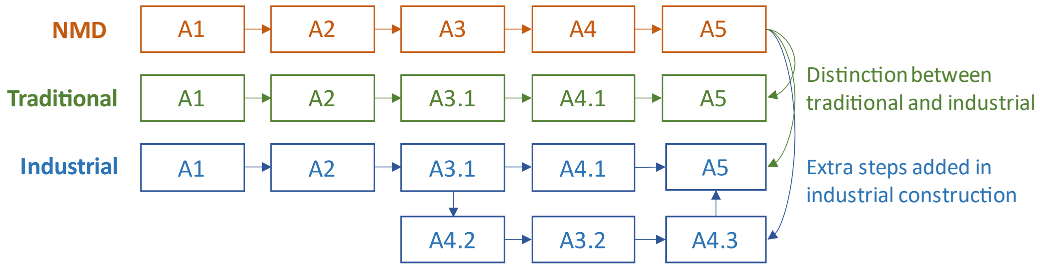


*Figure 8 Module A of the MPG calculation according to the NMD and as applied in this study*

The differences that are currently not adequately reflected in the MPG calculation (transport and machinery, construction waste and the construction of the housing factory) will be further examined in Phase II. Besides those differences, the adapted MPG calculation (Figure 8) will be used in Phase II to quantify them.

### 4.3 Observations Phase I: Identifying differences

The first observation is that the current MPG calculation does not distinguish traditional and industrial-constructed houses unless industrial construction firms produce Category-1 data environmental profiles. However, this is a time-consuming and costly process and thus often not feasible for innovative construction products.

The second observation is that the results of the interviews indicate that sustainability is not a priority in industrial construction. Industrial construction is initially used to save time and money. The expected sustainability benefits are perceived to be a secondary advantage. Therefore, sustainability needs to yield profit for the construction firms or should be mandated by the Dutch National government.

The last observation is that due to the issues with the MPG, several other concepts arise in the construction sector to prove sustainability (e.g. BCI, MPG-2, EPG or NZEB). However, this has led to confusion among clients who are unsure of what they are asking for. While the MPG was intended to fulfil the role of a unified method for calculating the environmental impact of houses, it has not been successful in doing so.

## 5. Case studies

This section aims to describe the case studies used to determine the potential benefit of industrial construction compared to traditional construction in $CO_2$ savings. Each case study consists of two comparable scenarios (a traditional and an industrial scenario).

It is important to note that the scenarios can be compared with each other, but the case studies cannot be compared. In other words, the results of Case A and B cannot be compared, but the results of Case A – the traditional and 3D industrial scenario – can be compared. This is due to different assumptions made during the creation of the models.

Table 1, Table 2 and Table 3 present the principles of the traditional and industrial scenarios for Cases A, B and C. The first column describes the method that was used. it is important to note that Case A compares a traditional construction scenario with a 3D industrial scenario, while Cases B and C compare a hybrid construction scenario with a 2D industrial scenario.

Hybrid construction is a combination of traditional and industrial construction, but for this study, it is classified as traditional construction. Therefore, when reading about traditional construction in this research report, it also includes hybrid construction.

*Table 1 Principles of the traditional and industrial scenario for Case A*

| **Method/scenario** | **Type** | **Bvo (per house)** |
|---|---|---|
| Traditional | 200 apartments | 25 $m^2$ |
| 3D industrial | 200 apartments | 25 $m^2$ |

*Table 2 Principles of the traditional and industrial scenario for Case B*

| **Method/scenario** | **Type** | **Bvo (per house)** |
|---|---|---|
| Hybrid (67% industrial)* | 17 row houses | 140 $m^2$ |
| 2D industrial | 15 row houses | 140 $m^2$ |

*Table 3 Principles of the traditional and industrial scenario for Case C*

| **Method/scenario** | **Type** | **Bvo (per house)** |
|---|---|---|
| Hybrid (67% industrial)* | 1 house | 165 $m^2$ |
| 2D industrial | 2 houses | 145 $m^2$ |

**The percentage of industrially produced elements in the hybrid scenarios for Cases B and C are coincidentally both 67%. This percentage is determined by the weight of the industrially produced elements.*

# 6. Creation and validation of the models

This section aims to describe the models created to calculate the $CO_2$ emissions belonging to transport and machinery, construction waste and the construction of the housing factory for traditional and industrial construction. Those calculated emissions are then used to determine the potential benefit of industrial construction in $CO_2$ savings.

This chapter describes the elaboration on each model and the validation and verification of the models. More information (data gaps, assumptions and sensitivity analysis) about the models are described in Appendix B.

**Elaboration on the created models**

The first model (Figure 9) calculates the $CO_2$ emissions belonging to transport and machinery for Cases A and B. The companies responsible for these cases had already calculated the $CO_2$ emissions for either Module A or Modules A-D. The remaining task was to convert these calculated $CO_2$ emissions to comparable data and validate and verify the model.

With these results, the differences between the construction methods and thus the potential benefit of industrial construction on transport and machinery in Cases A and B can be calculated. These results are calculated in $kgCO_2$ per scenario and $kgCO_2/m^2$bvo. The differences between the construction methods are calculated in $kgCO_2$ per scenario, $kgCO_2/m^2$bvo and in percentages.

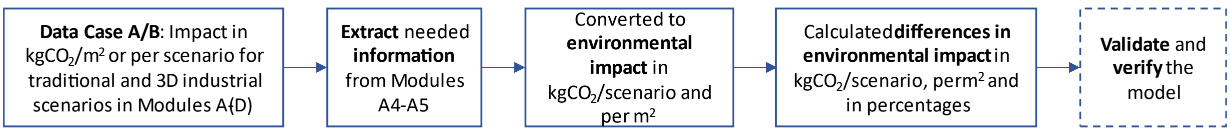


*Figure 9 Steps taken to calculate the impact of transport and machinery in Cases A and B*

The second model (Figure 10) calculates the $CO_2$ emissions belonging to transport and machinery for the Scenarios of Case C. The company responsible for this case did not make calculations on the $CO_2$ emissions, but solely delivered technical drawings and a list of the materials used to calculate the MPG score.

By adding the calculated $CO_2$ emissions belonging to the transport of materials, staff and machinery, the total environmental impact of transport, and thus in A4.1, A4.2 and A4.3 was calculated. The $CO_2$ emissions belonging to the transport of machinery to the factory is included in the impact of the construction of the housing factory. These calculations were based on the technical drawings, the list of materials used, interviews with work planners to fill data gaps and make assumptions, data from EcoInvent and data from CO2emissiefactoren.nl.

The $CO_2$ emissions belonging to the energy consumption of the factory and on the construction site of the scenarios in Case C were calculated based on data gathered from interviews, CO2emissiefactoren.nl and previous Cases.

Certain companies produce wood or concrete for themselves instead of importing these materials from other factories. The transportation of these materials to the factory is not included in the calculation, as it is also not accounted for in traditional construction. The energy consumption required for production is included in the calculation in A3.2.

Adding the calculated $CO_2$ emissions of Modules A4.1, A3.2, A4.2, A4.3 and A5 in $kgCO_2$/scenario results in the total environmental impact for both (traditional and industrial) scenarios.

With these results, the differences between the construction methods and thus the potential benefit of industrial construction on transport and machinery in Case can be calculated. These results are calculated in $kgCO_2$ per scenario and $kgCO_2/m^2$bvo. The differences between the construction methods are calculated in $kgCO_2$ per scenario, $kgCO_2/m^2$bvo and in percentages.

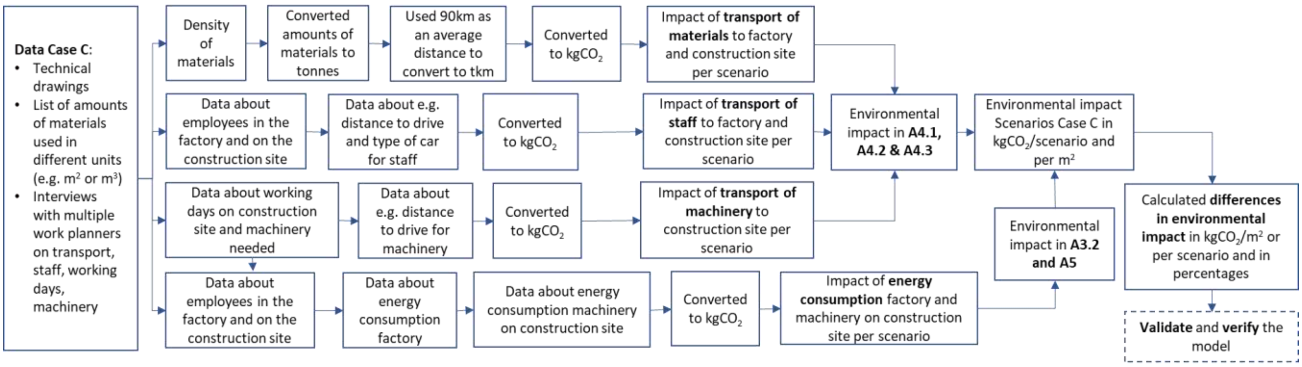


*Figure 10 Steps taken to calculate the impact of transport and machinery in Case C*

The third model (Figure 11) calculates the $CO_2$ emissions belonging to construction waste. First, the amounts of construction waste arising in the cases were calculated and converted to the impact of transporting and processing construction waste in $kgCO_2$/scenario.

The differences in amounts of construction waste between the scenarios (in kg waste) were then used to calculate the $CO_2$ emissions that could have been avoided when choosing industrial construction instead of traditional construction.

Data on the average substations of construction waste was used to determine the different materials that would have otherwise ended up as waste. Data from EcoInvent on producing those materials was used to calculate the CO2 emissions belonging to producing those materials.

Since there are multiple types of wood and the impact of producing this differs significantly, a bandwidth was used for this part. The results in this report present the most negative scenario for industrial construction. In other words, differences between the construction methods might only be greater. The calculated possible avoided $CO_2$ emissions were added to the $CO_2$ emissions from transporting and processing the construction waste of traditional construction.

With these results, the differences between the construction methods and thus the potential benefit of industrial construction on construction waste in all cases can be calculated. These results are calculated in $kgCO_2$ per scenario and $kgCO_2/m^2$bvo. The differences between the construction methods are calculated in $kgCO_2$ per scenario, $kgCO_2/m^2$bvo and in percentages.

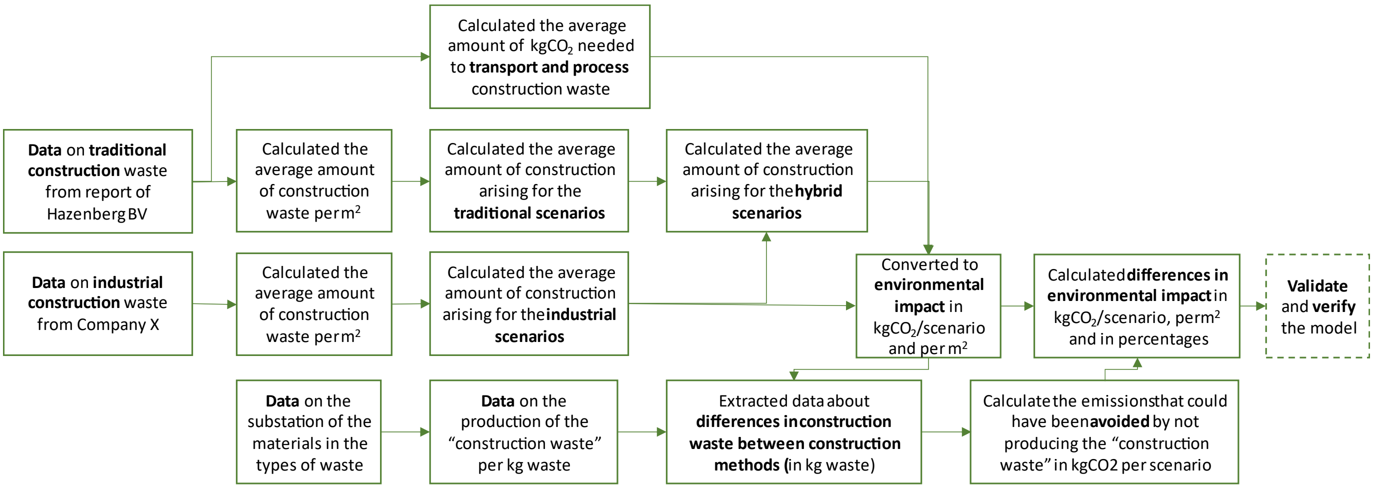


*Figure 11 Steps taken to calculate the impact of construction waste*

The fourth model (Figure 12) calculates the $CO_2$ emissions belonging to the construction of the housing factory. Exact data on the impact of the construction of the factory was hard to collect since it was not available or confidential. Therefore, data from EcoInvent on the construction of factories that share similarities with housing factories including installations was used.

The average amount of $CO_2$ emissions belonging to the construction of three types of those factories ($kgCO_2/m^2$ factory hall), the size of the particular housing factory ($m^2$), the annual production (houses/year) and the expected lifespan (years) were used to calculate the environmental impact of the produced houses.

With these results, the differences between the construction methods and thus the potential drawback of industrial construction on the construction of the housing factory in all cases can be calculated. These results are calculated in $kgCO_2$ per scenario and $kgCO_2/m^2$bvo. The differences between the construction methods are calculated in $kgCO_2$ per scenario, $kgCO_2/m^2$bvo and in percentages.

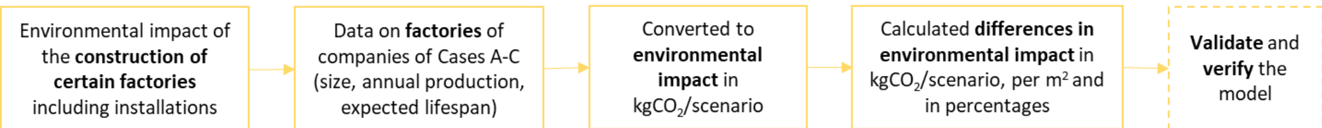


*Figure 12 Steps taken to calculate the impact of the construction of the housing factory*

The last, and fifth, model (Figure 12) summarises the aforementioned models. It adds on the calculated $CO_2$ emissions of transport and machinery, construction waste and the construction of the housing factory. When adding those, a comparison between the construction methods can be made.

With these results, the potential benefit of industrial construction on all three topics and all cases can be determined. These results are presented in $kgCO_2$ per scenario and $kgCO_2/m^2$bvo The differences are presented in $kgCO_2$ per scenario, $kgCO_2/m^2$bvo and in percentages.

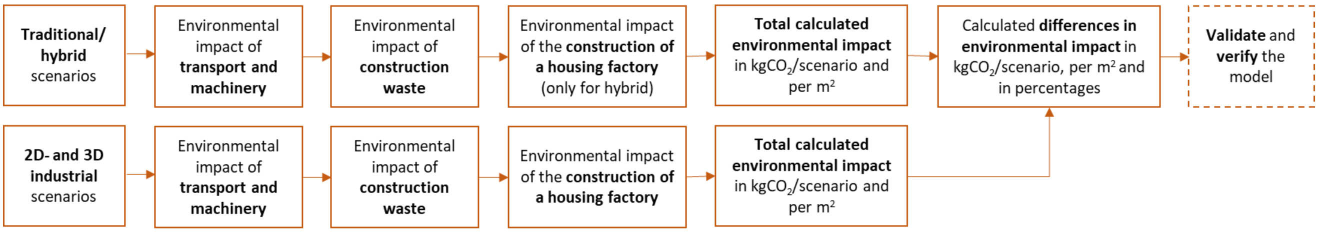


*Figure 13 Steps taken to calculate the total environmental impact*

**Validation and verifying of the models**

The validation of the models was done by checking whether the models could help with answering the main question. The main question is about the potential benefit of industrial construction compared to traditional construction in terms of $CO_2$ savings. The final, and fifth, model presents the differences between the calculated environmental impact for transport, machinery, construction waste and the construction of the housing factory. These results help in answering the main question.

The verification methods as described in Chapter 3.4 were conducted and checked whether the models were built correctly. The models are based on the MPG calculation, which is a validated method. The results of the models were compared with the results of the other models. For example, for Cases A and B certain calculations were already made. The results of Case C were then compared with those results. When large differences appeared, they were checked.

The models were also checked by experts in the field. An LCA expert from Copper8 was asked for advice when something remarkable happened. Another expert in the construction sector was asked for advice, for example on how to determine the impact of the factory due to a lack of data. The results of this part were compared with literature on the calculated environmental impact of housing factories without installations.

There was little scientific literature on the subject. Where it was possible to compare with real data, this was done. However, this was not done very often. This was easier for the traditional scenarios than for the industrial scenarios.

An extreme test was to check the model formulas in Excel. This verification process revealed some errors. After correcting these errors, the models were verified.

## 7. Results Phase II: Overviews

This section presents overviews of transport and machinery and construction waste for traditional and industrial construction. The overviews aim to provide a more detailed version of those topics in the Construction Phase (Modules A4-A5) of the MPG method and to visualise the differences between the construction methods.

### Transport and machinery

Figure 14 provides an overview of transport and machinery in the Construction Phase (A4-A5) of traditional construction (Figure 8). The environmental impact of transport movements (of staff, machinery and construction products) to the construction site is calculated in A4.1. The environmental impact of the construction process is calculated in A5.

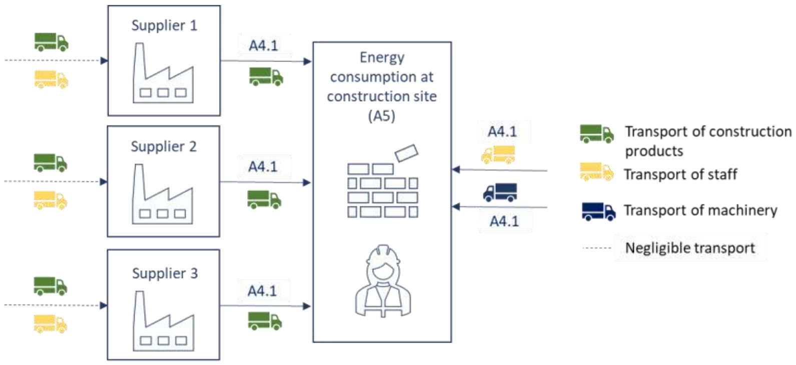


*Figure 14 Overview of transport and machinery in Modules A4 – A5 of traditional construction*

Figure 15 provides an overview of transport and machinery in the Construction Phase (A4-A5) of industrial construction (Figure 8). The composition of Modules A4.1 and A5 is the same as in traditional construction. The difference is that the majority of construction products are not transported directly to the construction site, but rather via the housing factory.

The impact of the transport movements (of staff and construction products) to the housing factory is calculated in Module A4.2. The housing factory produces 2D and 3D elements, which are then transported to the construction site. The environmental impact of this production is calculated in A3.2 and the impact of this transportation to the construction site is calculated in A4.3.

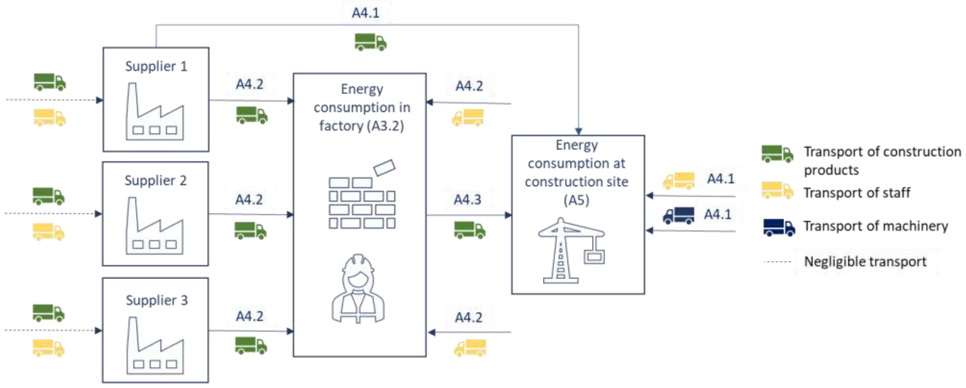


*Figure 15 Overview of transport and machinery in Modules A4-A5 of industrial construction*

These overviews aim to provide a deeper understanding of the differences in transport and machinery between the construction methods. They will also serve as the foundation for models that aim to calculate the $CO_2$ emissions belonging to transport and machinery in the scenarios (Chapter 8).

The difference between the construction methods when looking at these overviews is the extra steps needed in industrial construction. Those extra steps describe the transport movements to the housing factory (A4.2), from the housing factory to the construction site (A4.3) and the energy consumption needed in the housing factory (A3.2). Similar to both construction methods are the transport movement to the construction site (A4.1) and the energy consumption on the construction site (A5).

**Construction waste**

Figure 16 provides an overview of construction waste in traditional construction in the Construction Phase (A4-A5) (Figure 8). The waste generated on construction sites originates from construction products, such as residual materials, cutting losses, breakage, and material damage, as well as packaging materials [14].

Waste prevention opportunities exist on construction sites, for example, through downcycling. The goal is to categorise waste on the construction site as described in Figure 16. In practice, this can be challenging as there may be limited space on the construction site for numerous containers, especially in urban areas [7].

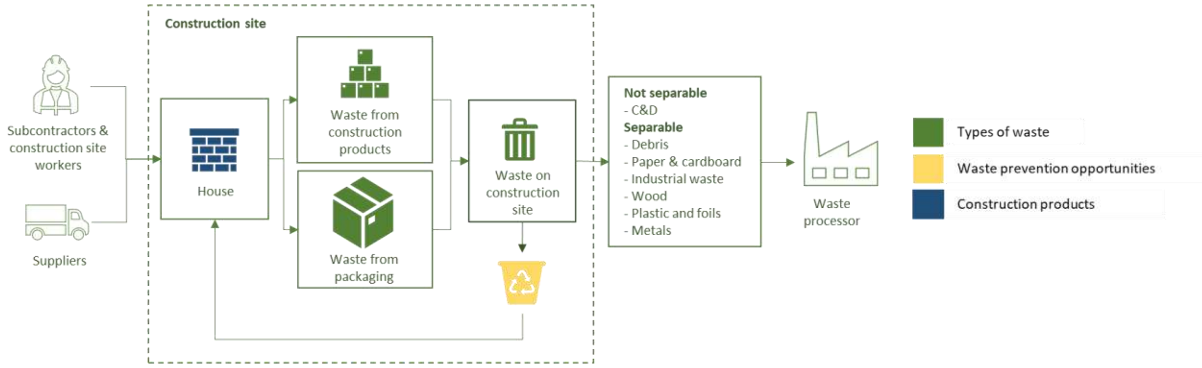


*Figure 16 Overview of construction waste in Modules A4 – A5 of traditional construction*

Figure 17 provides an overview of construction waste in industrial construction in the Construction Phase (A4-A5) (Figure 8). Similar to traditional construction, the waste generated on construction sites originates from construction products, such as residual materials, cutting losses, breakage, and material damage, as well as packaging materials.

There are three opportunities to prevent waste in industrial construction. The first opportunity arises for suppliers, they can take back their residual waste and bring it back into their supply chain [7]. This is something that factories also do themselves to prevent waste (the second opportunity to prevent waste) [7]. The third opportunity to prevent waste is to downcycle on the construction site. However, as the majority of the construction process takes place in the housing factory, there is relatively little waste left on the construction site.

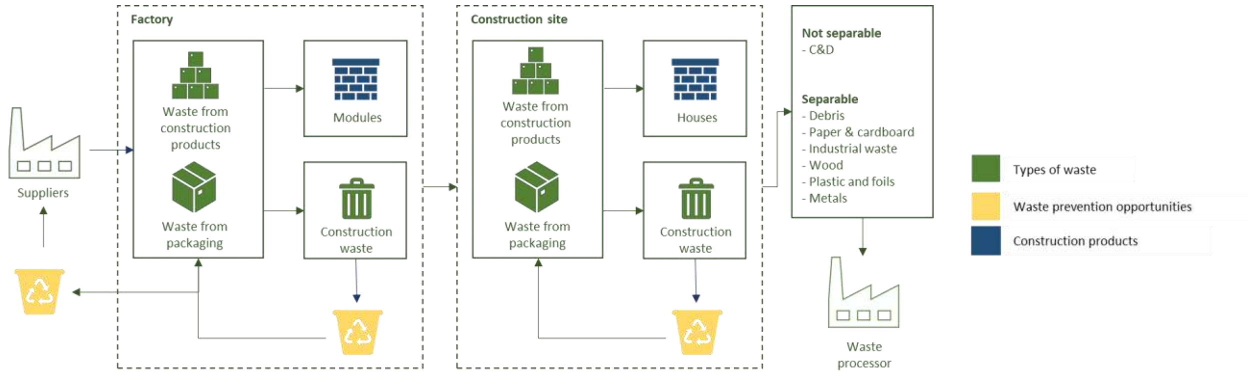


*Figure 17 Overview of construction waste in Modules A4 – A5 of industrial construction*

These overviews aim to provide a deeper understanding of the differences in construction waste between the construction methods. They will also serve as the foundation for models that aim to calculate the $CO_2$ emissions belonging to construction waste in the scenarios (Chapter 8).

The difference between the construction methods when looking at these overviews is the extra possibilities to prevent waste, namely by suppliers, in the factory and on the construction site. Similar in both overviews, are the types of waste arising. The difference is that it is easier to separate waste in a factory compared to traditional construction, especially when constructing in urban areas since there might be a lack of space for waste containers in urban areas.

# 8. Results Phase II: Potential $CO_2$ savings industrial construction

To determine the potential environmental benefit of industrial housing production in $CO_2$ savings, a comparison was made with traditional housing production. This comparison was made between the impact of transport and machinery, construction waste and the construction of the housing factory in the Construction Phase of the MPG calculation for traditional and industrial construction.

This chapter begins with the results for Cases A, B and C (8.1, 8.2 and 8.3) and closes with observations made based on the results of all three cases (8.4).

## 8.1 Case A

Case A aims to compare a traditional scenario with a 3D industrial scenario. The results of this comparison are presented in Table 4. It shows the calculated $CO_2$ emissions belonging to transport, machinery, construction waste and the construction of the housing factory (accounts solely for industrial construction) in the Construction Phase of the MPG calculation for traditional and industrial construction.

Results of Case A indicate that a reduction of 49% of $CO_2$ emissions could be achieved for 3D industrial construction compared to traditional construction.

*Table 4 Results comparison Case A*

| | Environmental impact ($kgCO_2$/scenario) | Environmental impact ($kgCO_2/m^2$bvo) |
|---|---|---|
| **Traditional** | 1,956 | 78 |
| **Industrial** | 997 | 40 |
| **Differences** | 959 (49%) | 38 (49%) |

Figure 18 presents the calculated environmental impact of Case A for both scenarios split up into the impact of transport and machinery, construction waste and, for industrial construction, the construction of the housing factory. There has been a significant reduction in carbon emissions in transport and machinery (from 71 to 38 $kgCO_2/m^2$bvo in favour of industrial construction).

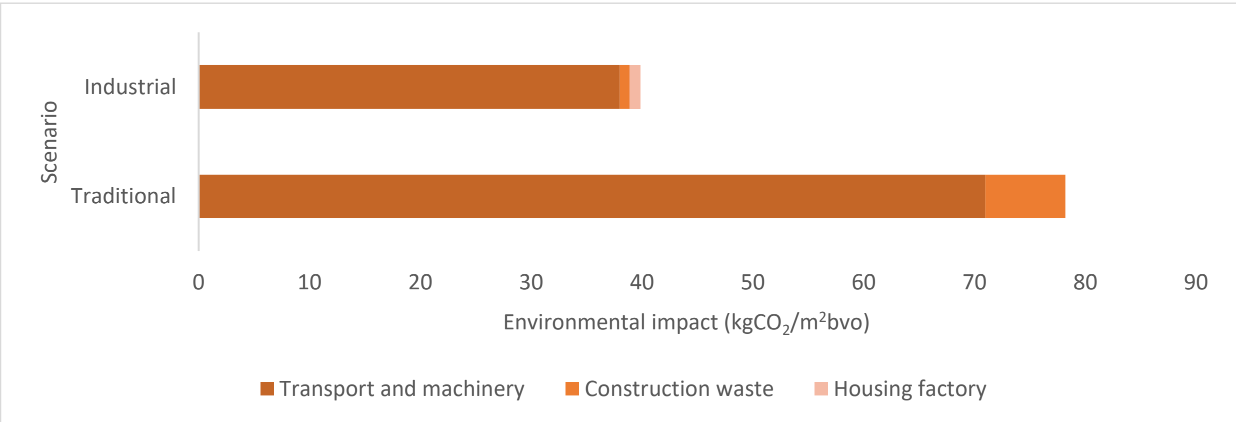


*Figure 18 Results of Case A split up into the environmental impact of the calculated topics*

The decrease in $CO_2$ emissions belonging to transport and machinery usage is primarily attributed to the impact arising in Modules A4.1 and A5 (Figure 19). The reduction in A4.1 is due to the transport movements being transferred to Modules A4.2 and 4.3. The reduction in A5 is due to the reduced time spent on the construction site since the biggest part of the construction process took place in the factory.

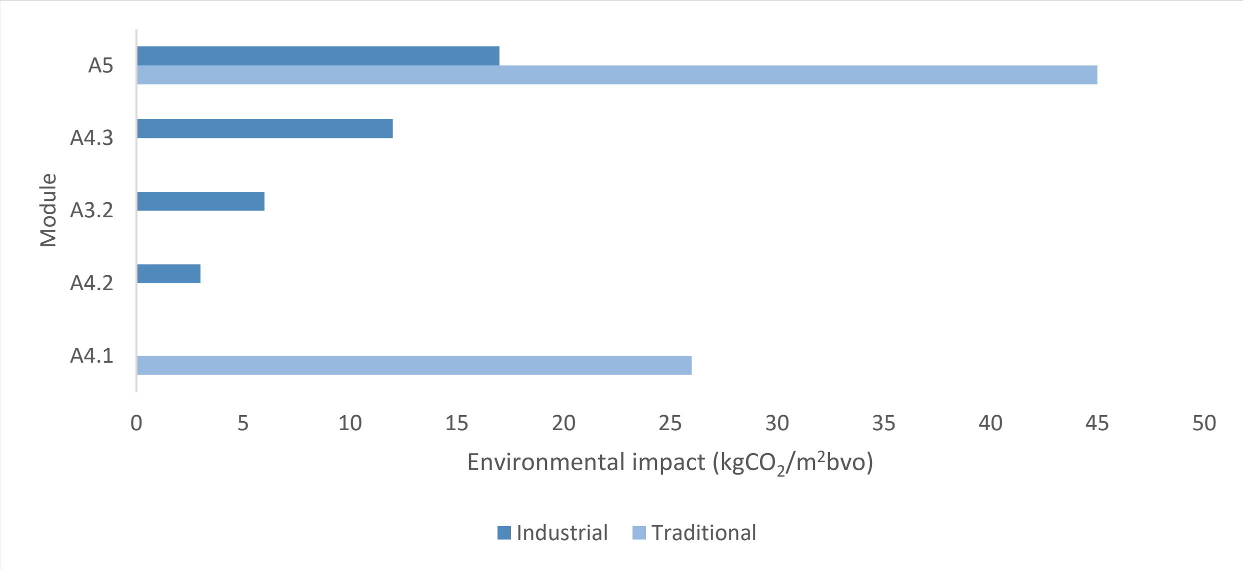


*Figure 19 Results of Case A split up into the environmental impact of the different Modules for transport and machinery*

Besides the reduction in transport and machinery, there also is a strong reduction in emissions coming from construction waste (from 7 to 1 $kgCO_2/m^2bvo$ in favour of industrial construction). The reduction in emissions coming from construction waste is on one side caused by the reduction of waste in industrial construction (due to the reasons described in Chapter 7). However, the biggest difference is caused by adding the possibly avoided emissions to the traditional case (Figure 20). In other words, avoiding waste has a greater impact than improving waste management.

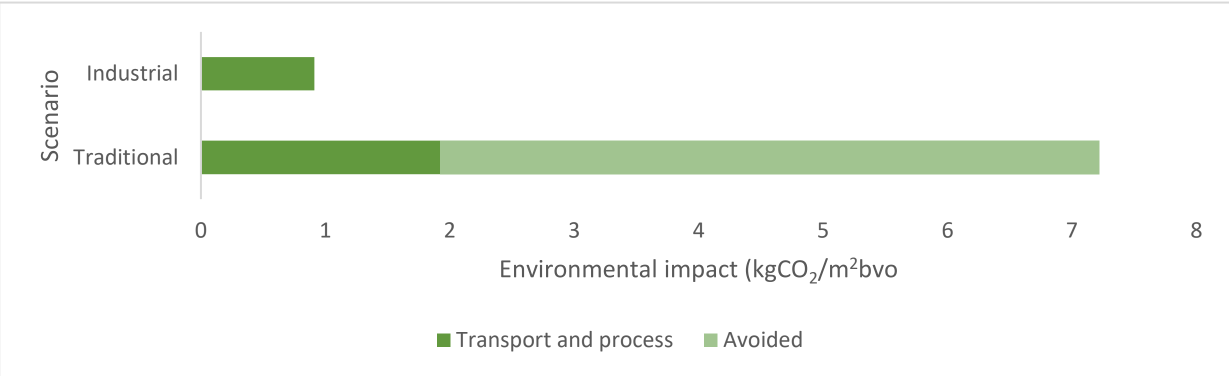


*Figure 20 Results of Case A split up into the environmental impact of transport and process construction waste and the avoided emissions*

The impact of the construction of the housing factory for traditional construction is zero since there is no housing factory included. The impact of the construction of the housing factory for industrial construction in Case A is 0.96 $kgCO_2/m^2bvo$.

When adding all the calculated CO2 emissions of transport and machinery, construction waste and the construction of the housing factory in the Construction Phase of the MPG calculation, the benefit of industrial construction is 38 $kgCO_2/m^2$bvo or a 49% reduction in $CO_2$ emissions per $m^2$bvo.

## 8.2 Case B

Case B aims to compare a hybrid scenario with a 2D industrial scenario. The results of this comparison are presented in Table 5. It shows the calculated $CO_2$ belonging to transport, machinery, construction waste and the construction of the housing factory in the Construction Phase of the MPG calculation for traditional and industrial construction.

Results of Case B indicate that a reduction of 33% of $CO_2$ emissions could be achieved for 2D industrial construction compared to hybrid construction.

*Table 5 Results comparison Case B*

| | Environmental impact ($kgCO_2$/scenario) | Environmental impact ($kgCO_2/m^2$bvo) |
|---|---|---|
| **Traditional** | 8,051 | 57 |
| **Industrial** | 5,366 | 38 |
| **Differences** | 2,684 (33%) | 38 (33%) |

Figure 21 presents the calculated environmental impact of Case B for both scenarios split up into the impact of transport and machinery, construction waste and the construction of the housing factory. As this Case compares hybrid construction to 2D industrial construction, the differences in transport and machinery are significantly smaller than in case A. The differences (1 $kgCO_2/m^2$bvo in favour of industrial construction) might not be significant enough to determine the most sustainable method on this topic.

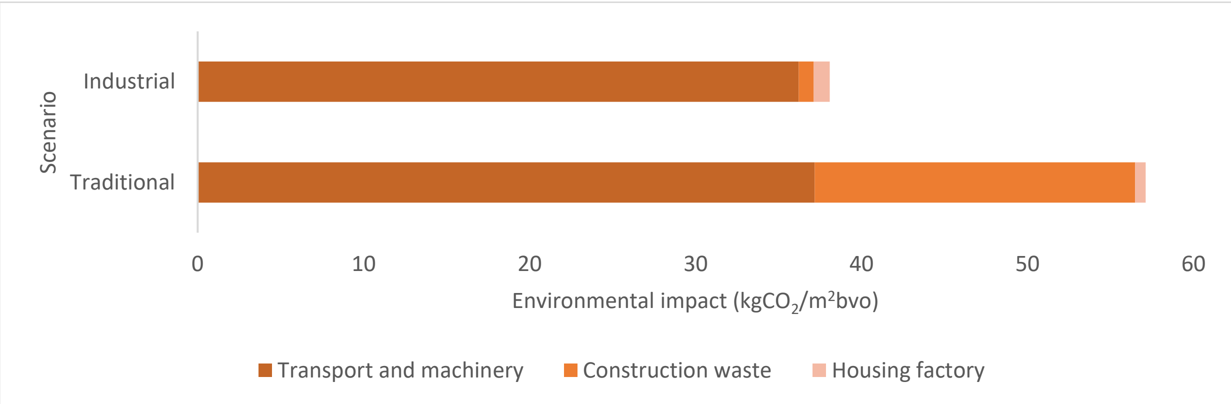


*Figure 21 Results of Case B split up into the environmental impact of the calculated topics*

Similar to Case A, the biggest decrease in $CO_2$ emissions on this topic is in Module A5 (Figure 22) due to the reduced time spent on the construction site. In contrast to the reduction in A5, the calculated $CO_2$ emissions in A3.2 (production of 2D elements in housing factory) increase significantly compared to traditional (or hybrid) construction. This can be explained by the fact that part of the construction process (A5) has been moved to the factory (A3.2) and thus the $CO_2$ emissions transfer from A5 to A3.2.

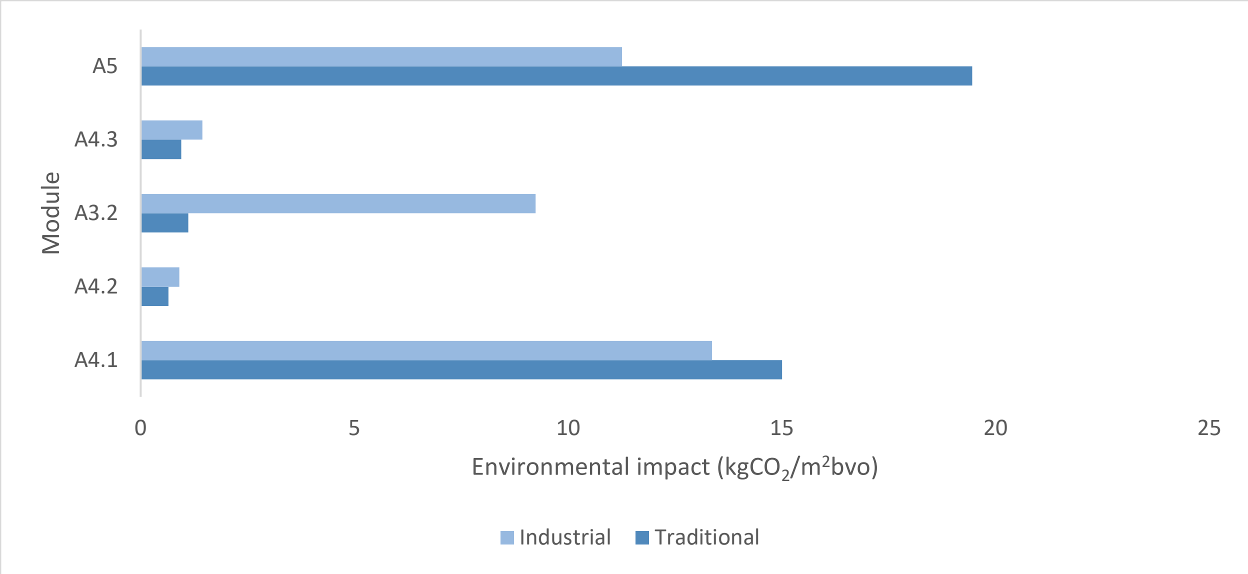


*Figure 22 Results of Case B split up into the environmental impact of the different Modules for transport and machinery*

However, when adding the calculated $CO_2$ emissions belonging to construction waste, the difference increases from 1 to 19 kg$CO_2$/m$^2$bvo in favour of industrial construction. The reduction in emissions coming from construction waste is, similar to Case A, mostly coming from the possible avoided emissions (Figure 23).

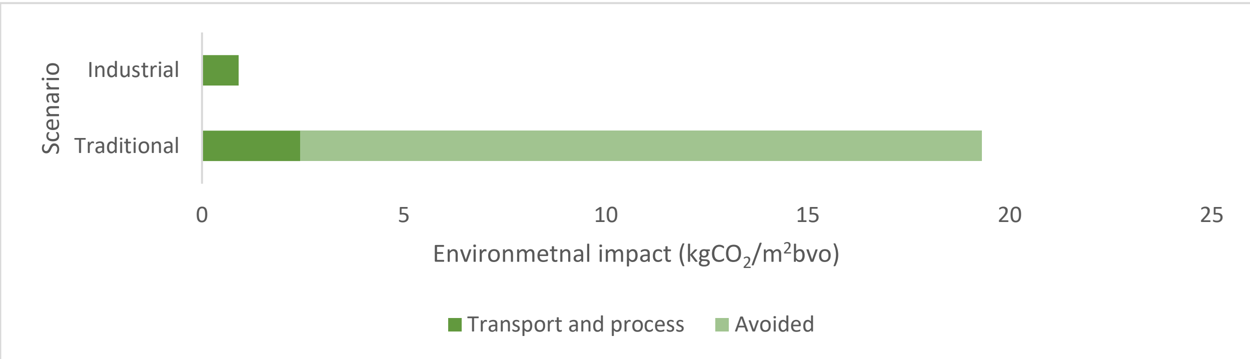


*Figure 23 Results of Case B split up into the environmental impact of transport and process construction waste and the avoided emissions*

Even when taking into account the calculated $CO_2$ emissions belonging to the construction of the housing factory, that have a negative effect on industrial construction (a difference of 0.32 kg$CO_2$/m$^2$bvo in favour of traditional construction), industrial construction still results in a total reduction of 33% in $CO_2$ emissions per m$^2$bvo or 38 kg$CO_2$/m$^2$bvo.

### 8.3 Case C

Case C aims to compare a hybrid scenario with a 2D industrial scenario. The results of this comparison are presented in Table 6. It shows the calculated $CO_2$ emissions belonging to transport and machinery, construction waste and the construction of the housing factory in the Construction Phase of the MPG calculation for traditional and industrial construction.

Results of Case C indicate that a reduction of 25% of $CO_2$ emissions could be achieved for 2D industrial construction compared to hybrid (or: traditional) construction.

*Table 6 Results comparison Case C*

| | Environmental impact ($kgCO_2$/scenario) | Environmental impact ($kgCO_2/m^2$bvo) |
|---|---|---|
| **Traditional** | 14,330 | 87 |
| **Industrial** | 9,502 | 66 |
| **Differences** | 4,828 (34%) | 21 (25%) |

Figure 24 presents the calculated $CO_2$ emissions of Case C for both scenarios split up into the impact of transport and machinery, construction waste and the construction of the housing factory.

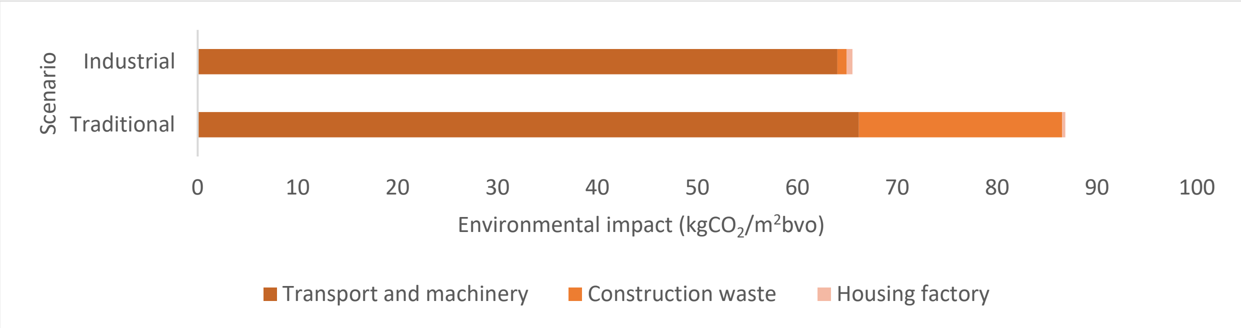


*Figure 24 Results of Case C split up into the environmental impact of the calculated topics*

Figure 25 presents the impact of transport and machinery divided into the different submodules. Other than Cases A and B, most of the $CO_2$ emissions are arising in Module A4.1. This is due to calculating the environmental impact of the transport of machinery. Similar to Cases A and B is the reduced impact in A5 due to the shortened construction time on the construction site. The reliability of the results on this topic may be lower compared to those of Case A and B due to the delivery of less data and the need for more assumptions.

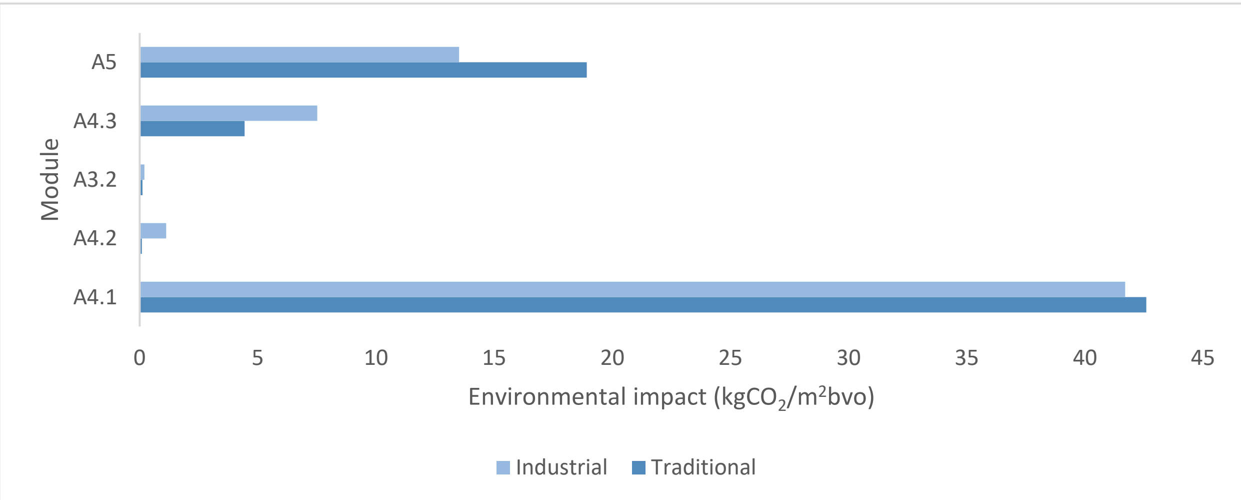


*Figure 25 Results of Case C split up into the environmental impact of the different Modules for transport and machinery*

Similar to Case B, the differences in transport and machinery (2 $kgCO_2/m^2$bvo in favour of industrial construction) might not be significant enough to determine the most sustainable method on this topic. However, when adding the calculated environmental impact of construction waste, the difference increases from 2 to 21 $kgCO_2/m^2$bvo in favour of industrial construction. The reduction in emissions coming from construction waste is, similar to Case A and B, for the biggest part coming from the possible avoided emissions.

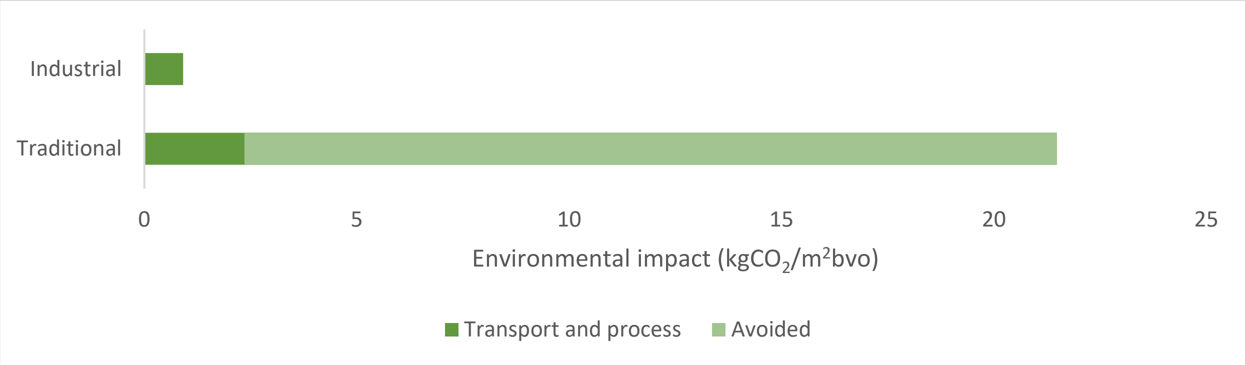


*Figure 26 Results of Case C split up into the environmental impact of transport and process construction waste and the possibly avoided emissions*

Even when taking into account the impact of the housing factory construction, which has a negative effect on industrial construction (a difference of 0.24 $kgCO_2/m^2$bvo in favour of traditional construction), industrial construction still results in a 25% reduction in $CO_2$ emissions per $m^2$bvo or 21 $kgCO_2/m^2$bvo.

### 8.4 Observations Phase II

The initial observation is that the Production Phase of the MPG calculation calculates the environmental impact at the product level and the Construction Phase at project level. Since every project is unique, it is hard to establish Environmental Profiles suitable for every project. Therefore, the impact of activities in the Construction Phase is often not calculated.

Additionally, the environmental impact of the Production Phase is greater than the Construction Phase. This statement implies that the choice of material may have a greater influence on the environmental impact than the choice of another construction method.

> *Quantifying* the currently insufficiently reflected differences between the construction methods in the *Construction Phase* leads to differences of *25-49% per $m^2$bvo.* Assuming that the environmental impact of the *Production Phase* is *similar* results in a difference in *$CO_2$ emissions* between the construction methods in *the Production and Construction Phase* of *6.6-10.6% per $m^2$bvo.*

The final observation is that the current MPG calculation is not accurate enough to determine the environmental effect of various construction methods. It can only be used to calculate the environmental impact of the materials used if accurate Category-1 Data is available. However, it still does not account for the impact of construction waste and the housing factory, while the previous results prove that there is a significant difference in environmental impact when calculating those topics.

## 9. Discussion and limitations

This section describes the discussion points, limitations and possibilities for further research. Data gaps occurring and assumptions made during the creation of the models are described in Appendix B. Discussion points on the MPG calculation are described in Chapter 4.1 and Appendix C.

**Discussion**

It is difficult to compare traditional and industrial construction, as each construction project is unique. As a result, it is almost impossible to provide accurate Category-1 environmental profiles that could help calculate the environmental impact of projects. These environmental profiles are not unique for each project but for each building product.

The construction firms delivered the calculated data for transport and machinery of Cases A and B, which only needed to be converted to comparable data. Assuming that the firms have all the necessary data, the results can be considered reliable. For Case C, only the technical drawings and an MPG calculation were delivered. Therefore, assumptions were made (elaborated on in Appendix B). This means that the results of this case are less reliable than those of Cases A and B, as not all the necessary data was available.

One of the reasons for conducting this research was the question of whether the environmental impact of the construction of a housing factory possibly has a greater impact than the reduction in environmental impact on the topics of transport, machinery, and construction waste. This perception is unfounded. The results indicate that the largest impact, by far, comes from the use of transport and machinery.

This outcome may be due to the limited data available on construction waste and the housing factory. The limited data is due to industrial construction being a relatively new subject [7] and therefore data being confidentially or simply not available. Due to the limited data, certain assumptions were made during the model's creation. Those assumptions are presented in Appendix B and could influence the results of the comparison. However, the results indicate such a large positive environmental benefit for industrial construction, it is not expected that this conclusion would change, but the exact results might.

The calculation of the impact of traditional construction waste is based on the average of three cases from 2022 and is thus considered reliable. However, the exact data on the amount of construction waste raised from the traditional scenarios was not available. Therefore, the average numbers on traditional construction waste from this report were used to calculate the environmental impact of the three traditional scenarios.

The same accounts for industrial construction waste. This data was coming from one factory and used for all three industrial scenarios. For lack of a better option, this was a satisfactory choice. In any case, it would be preferable to use the exact data for each scenario.

Multiple interviews were conducted in this research to identify the key stakeholders, opportunities, and barriers to reducing the environmental impact of industrial construction. The results provide recommendations for stakeholders. However, it is important to note that only sustainability experts and work planners from construction firms, as well as a work planner from a transport company, were interviewed due to time constraints. If more key stakeholders were interviewed, the results of the final chapter (Recommendations) may differ.

**Limitations**

Performing an LCA is an often-used method to calculate the impact of a product (in this case a house). However, performing an LCA involves uncertainties. This is because construction firms often do not know exactly the amount of transport movements, the amount of construction waste, etc. But also since assumptions were made to calculate the environmental impact in $kgCO_2$.

Companies may be hesitant to share their information, which is understandable as it is often confidential and requires significant investment. However, sharing data could lead to more accurate results and may lead to an accelerated transition to a more sustainable construction sector. In particular, there was limited data shared in the field of calculating the impact of constructing the factory.

Finally, it is also important to note that results show the differences in environmental impact between the construction methods on the currently insufficiently reflected topics in the MPG calculation. Results of Phase I show that these differences have to do with transport, machinery, construction waste and the housing factory. This study does not consider other possible differences in environmental impact in Module A. This may lead to different results.

# 10. Conclusion

This section aims to describe the conclusions that can be drawn based on the results of Phase I and II.

The current MPG calculation does not distinguish between traditional and industrial-constructed houses. This is due to the lack of certain topics that do differ in their environmental impact when looking at traditional and industrial construction, but are currently not calculated in the MPG calculation.

The currently insufficiently reflected topics that in theory influence the MPG score and thus could result in a different environmental impact for traditional and industrial construction are:

- The impact of transport and machinery (+);
- The impact of construction waste (+);
- The impact of constructing a housing factory (-).

Another result of Phase I is an adapted MPG calculation as presented in Figure 8. This calculation is used to quantify the identified insufficiently reflected topics in the current MPG calculation and to answer the main question, which is as follows:

> *What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction when focusing on the currently insufficiently reflected topics in the Production and Construction phase of the MPG calculation?*

The benefit of industrial construction in the Construction Phase of the MPG calculation for transport and machinery, construction waste and the construction of a housing factory is a reduction of 25-53% in $kgCO_2$ per $m^2$bvo (or 21-38 $kgCO_2/m^2$bvo). This is dependent on the construction method of the scenarios. The differences in $CO_2$ emissions between traditional and 3D industrial construction are, in fact, larger than the differences between hybrid and 2D industrial construction.

Another conclusion that can be drawn based on the results of Phase II is that the Production Phase of the MPG calculation calculates the environmental impact on product level and the Construction Phase at project level. Additionally, the environmental impact of the Production Phase is higher than the Construction Phase, implying that the choice of material may have a greater impact than the construction method. Lastly, the current MPG is not accurate enough to determine the environmental impact of different construction methods, it can be used to calculate the environmental impact of materials used in a building when accurate Category-1 data is available in the NMD.

## 11. Recommendations

This section describes recommendations for reducing the environmental impact of industrial construction. These recommendations are a result of the research conducted in Phase III - Recommendations for key stakeholders.

The key stakeholders identified are [7]:

- **Industrial construction firms**: responsible for the construction process;
- **The government**: responsible for (monitoring) regulations;
- **The NMD**: responsible for the environmental profiles database;
- **Clients**: responsible for encouraging firms to achieve higher levels of sustainability performance;
- **Suppliers**: responsible for delivering sustainable (biobased or secondary) materials to the housing factory.

The main barrier to reducing the environmental impact of industrial construction is the current economic system [7]. It seems that to reduce the environmental impact of industrial construction, it should be made compulsory or yield profit. Other barriers to reducing the environmental impact of industrial construction have to do with:

**The government its regulations and monitoring on the MPG and sustainability** [7]: since it seems that reducing the environmental impact should be mandatory or yield profit, some said that more guidance from the national government is needed to lower the required MPG. Currently, there are no checks from the regional government on whether the houses built comply with the MPG calculation submitted.

**The communication and issues around the MPG calculation** [7]**:** multiple issues with the MPG were mentioned during the interviews. Elaboration on this topic can be found in Chapter 4.1 and Appendix C. The issues had mainly to do with communication from the NMD and the data quality of the Environmental Profiles.

**Technical development of transport alternatives for diesel trucks** [7]: the use of electric trucks and cranes as an alternative to diesel has some drawbacks. For instance, while a diesel truck can make up to nine trips a day, an electric truck may only manage one due to battery limitations. Additionally, there are concerns about the ability of an electric crane to lift a concrete 3D module.

**Innovation** [7]: the progress towards making the construction sector more sustainable has been slow. Although there are many innovative solutions, these have not been applied at scale due to the lack of demand.

**Financial barriers** [7]: new solutions like bio-based materials, innovative concrete, electrified transport and machinery can contribute to reducing environmental impact, but are currently more expensive than the traditional alternative. Due to the price-driven nature of this sector, this is a major barrier to becoming more sustainable.

Based on these aforementioned barriers, recommendations for the key stakeholders to overcome barriers in reducing the environmental impact of industrial construction were provided. These recommendations are shown in Table 7. The barriers are indicated by keywords in the first column, followed by the recommendation and the key stakeholders.

*Table 7 Recommendations for key stakeholders to overcome barriers in reducing the environmental impact of industrial construction*

| Barrier | Recommendation | Stakeholders |
|---:|---|---|
| Need for stricter regulations government | The national government should require stricter regulations around the sustainability of residential buildings that stimulate construction firms to reduce the environmental impact of industrial construction. | National government |
| No monitoring of the MPG score | The regional government should monitor whether the delivered MPG is built;<br>Construction firms should be more transparent about their MPG calculation and the final constructed house. | Regional government & industrial construction firms |
| Data-quality NMD could be better | Improve the MPG calculation for industrial-constructed residential buildings by for example implementing the topics calculated in this study*;<br>Industrial construction firms should establish LCAs to produce Category-1 data of their produced elements. | The NMD & industrial construction firms |
| Communication NMD could be better | The NMD should communicate in advance before deleting environmental profiles. This will allow construction firms to prepare themselves and prevent sudden reductions in the MPG. | The NMD |
| The fact that innovation is there, but not implemented yet | Clients should invest in projects that use sustainable materials and challenge construction firms to reduce the environmental impact of the houses they build;<br>Industrial construction firms should invest the money saved in sustainable materials**;<br>Suppliers should offer a variety of sustainable materials, whenever possible with guarantees. | Clients, industrial construction firms and suppliers. |

**The downside of this recommendation, is that this study researched the topics that are currently perceived to be insufficiently reflected in the MPG. A risk arises that when calculating these topics in an LCA, the environmental profiles will be higher than the traditional alternative. Unless the traditional alternative also calculates these topics.*

***Sustainable materials are materials with a reduced environmental impact compared to their traditional alternative (e.g. biobased or secondary materials).*

The most opportunities arise for industrial construction firms themselves. Often mentioned opportunities (from the interviews) in reducing the environmental impact of industrial construction are:

**Alternatives for diesel trucks** [7]: results of Phase II indicate that a significant proportion of $CO_2$ emissions originate from transport and machinery, primarily due to the use of diesel trucks and cranes. There are several alternatives to this current mode of transportation, such as electrified or hydrogen-based options.

**Implementing sustainable materials** [7]: a conclusion of Phase II is that a significant proportion of $CO_2$ emissions originate in Modules A1-A3. This statement suggests that the selection of a particular material may have a more significant effect than the choice of construction method. This means that when sustainable materials (e.g. biobased or secondary) are conducted in a building, the environmental impact could reduce significantly. The transfer to sustainable materials is easier to make in a factory, due to the conditioned circumstances;

**Implementing renewable energy sources in the housing factory** [7]**:** it is easier to ensure the use of renewable energy sources in industrial construction, as the entire process can run on green energy. Additionally, installing solar panels on the roof of a factory is easier than doing so temporarily on a construction site.

**Further optimisation of waste management** [7]**:** results of Phase II indicate that waste management is easier in industrial construction. Not all factories already implemented this management. Options for optimising waste management are:

- The separation of waste being easier due to more space for waste containers and not working with many sub-contractors;
- Suppliers and industrial construction firms have the opportunity to take back their residual materials and re-implementing them in their supply chain;
- Industrial construction firms having the opportunity to invest for example a particular saw that almost eliminates sawdust;
- Industrial construction firms have the opportunity to reuse sawdust for heating the factory.

# 12. Options for further research

Based on the discussion points and limitations described in Chapter 9, it is recommended to research what adaptations are required to use the MPG calculation in industrial construction. On one side, industrial construction firms could establish Category-1 data for their produced elements. However, this research shows that construction waste and the construction of the housing factory also have a certain impact, which is currently not included in the environmental profiles used in the MPG calculation.

Secondly, research could be conducted into whether there is a tipping point where hybrid construction emerges with a lower environmental impact than 2D construction. The size of the project or the percentage of sustainable (biobased or secondary) materials could influence this result.

Lastly, it is recommended to research how the regional government can monitor whether construction firms are building houses according to the calculated MPG score or how construction firms can be forced to be more transparent about their MPG scores. Currently, there is no monitoring to ensure that the delivered MPG is being built. This means that a building could be very sustainable on paper, but in reality, it may consist of different materials resulting in a higher environmental impact.

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## Appendix A - List of interviews, companies and gathered data

The table below shows a list of interviewees, what kind of firm they work at and what the objective was of the interview.

| | Person | Firm | Objective of the interview |
|---|---|---|---|
| A | Sustainability expert | Construction firm (traditionally & industrially) with their own factory. | Differences between construction methods + opportunities/barriers for industrial construction firms in reducing their environmental footprint. |
| B | Sustainability expert | Construction firm (traditionally & industrially) with their own factory. | What barriers the MPG calculation brings along + opportunities/barriers for industrial construction firms in reducing their environmental footprint. |
| C | Manager in sustainable housing | Construction firm (traditionally & industrially) with their own factory. | Differences between construction methods, struggles with the MPG + opportunities/barriers for industrial construction firms in reducing their environmental footprint. |
| D | Manager in sustainability | Construction firm (traditionally & industrially) without their own factory. | Differences between construction methods, struggles with the MPG + opportunities/barriers for industrial construction firms in reducing their environmental footprint. |
| E | Project manager R&D | Construction firm (industrially) with their own factory. | Issues with the MPG, differences in $CO_2$ emissions between traditional and industrial construction in transport and machinery. |
| F | Production manager | Construction firm (traditionally & industrially) with their own factory, works in the factory. | Differences in construction methods, main focus on construction waste. |
| G | Work planner | Transport company that arranges transport of traditional and industrial construction. | Differences in construction methods, main focus on transport. |
| H | Work planner | Construction firm (traditionally & industrially) with their own factory, works on site. | Gathering information for Case C about the planning in order to make calculations for transport and machinery. |

These interviewees work at different companies. Those companies also delivered data, not only in the form interviews, but also theses, practical data and company visits. The table below presents the companies (anonymous) and what data they delivered.

| **Company** | **Transport + machinery** | | **Construction waste** | | **Company visit** | **Cases** |
|---|---|---|---|---|---|---|
| | *Traditional* | *Industrial* | *Traditional* | *Industrial* | | |
| A | Report | Report | | Interview | Yes | |
| B | Interview | Interview | Practical data | | No | Case C |
| C | Report | Report | | Practical data | Yes | Case A |
| D | Report | Report | | | No | Case B |
| E | Interview | Interview | | | Yes | |
| F | | | Report | | No | |

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# Appendix B – Elaboration on the models

Models created to compare the environmental impact of traditional and industrial construction methods

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15-3-2024

## Table of content

# 1. Introduction

This appendix contains an elaboration on the models created in Excel to answer the main question of the thesis “Potential benefit of industrial construction in $CO_2$ savings – A comparison between traditional and industrial construction and possibilities to reduce the environmental impact of industrial construction”.

This main question is as follows:

> *What is the potential benefit in $CO_2$ savings of industrial construction compared to traditional construction when focusing on the currently insufficiently reflected topics in the Production and Construction phase of the MPG calculation?*

The models created aim to calculate the $CO_2$ emissions belonging to the three topics that are currently considered insufficiently reflected in the MPG (Environmental Performance of Buildings). These topics are transport and machinery, construction waste and the construction of the factory required for hybrid and industrial construction.

This report consists of the following chapters:

- 2 Impact of transport & machinery for Cases A and B;
- 3 Impact of transport & machinery for Case C;
- 4 Impact of construction waste for all cases;
- 5 Impact of the construction of the factory for all cases.

Each chapter describes the data gaps, the assumptions and the sensitivity analysis (when needed) for the model created.

## 2. Impact of transport and machinery for Cases A and B

This first model aims to calculate the $CO_2$ emissions belonging to transport and machinery in Cases A and B. Case A consists of a traditional and a 3D industrial scenario and Case B consists of a hybrid and a 2D industrial scenario. For this topic and these cases, the companies delivered calculated $CO_2$ emissions. Therefore, the only thing that remained to be done was extracting the data and converting those numbers to comparable data.

### Assumptions Case A (transport & machinery)

According to the report of the construction firm that delivered Case A, the following assumptions were made:

- An average driving distance of 66km;
- Commuting and transport of machinery is assumed to be the same in traditional and 3D-industrial construction;
- Assumptions have been made about the transportation of subcontractors;
- Amount of deliveries is divided by the maximum capacity of a truck for the specific material;
- Contact suppliers when lack of information about the deliveries.

### Sensitivity analysis Case A (transport & machinery)

For this topic and these cases, no sensitivity analysis was conducted. The emissions have already been calculated by other companies and stated, so no sensitivity analysis was needed.

### Assumptions Case B (transport & machinery)

According to the report of the construction firm that delivered this case study, the following assumptions were made:

- Commuting and transport of machinery is assumed to be the same in hybrid and 2D industrial construction.

### Sensitivity analysis Case B (transport & machinery)

Figure 1 presents the result of the sensitivity analysis conducted for the emission factors. These factors are originally from TNO, but multiple databases are presenting other factors. Therefore a sensitivity analysis for those emission factors has been conducted and tested the influence on the differences in $kgCO_2$/house.

| Transport and machinery - Sensitivity analysis Case B | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | Unit | | 25% | 50% | 100% | 150% | 200% | |
| Emissions/tkm | kgCO2/tkm | -69% | 42 | 74 | 137 | 200 | 264 | 93% |
| Emissions/kWh | kgCO2/kWh | 232% | 455 | 349 | 137 | -75 | -286 | -309% |
| Emissions/nm3 gas | kgCO2/nm3 | 0% | 137 | 137 | 137 | 137 | 137 | 0% |
| Emissions/Hour (crane) | kgCO2/hour | 0% | 137 | 137 | 137 | 137 | 137 | 0% |
| Emissions/km (subcontractors) | kgCO2/km | -237% | -188 | -80 | 137 | 354 | 571 | 317% |

*Figure 1 The sensitivity analysis results for the variables used to calculate the impact of transport and machinery in Case B*

The sensitivity analysis shows the following (from biggest to lowest impact):

- **Emissions/km (subcontractors)**: the higher this number, the bigger the differences between the construction methods in favour of 2D industrial construction. This means that when transport is electrified, this will work well for hybrid construction since the differences will become smaller;
- **Emissions/kWh (electricity factory)**: the smaller this number, the bigger the differences between the construction methods in favour of industrial construction. Meaning that when using renewable energy in the factory, this will be a major win for industrial construction;
- **Emissions/tkm (transport of materials):** the higher this number, the bigger the differences between the construction methods in favour of industrial construction, meaning that when transport is electrified, this will work well for hybrid construction since the differences will become smaller;
- **Emissions/hour (crane):** no differences are shown since the number of working hours of the crane is assumed to be the same for both cases;
- **Emissions/nm3 gas (gas usage factory)**: no differences are shown since there are no differences between the construction methods in the gas usage.

## 3. Impact of transport and machinery for Case C

This second model aims to calculate the $CO_2$ emissions belonging to transport and machinery in Case C, consisting of one hybrid and one 3D industrial project. In this case, the only data received were technical drawings and a list of materials used.

**Data gaps Case C (transport & machinery)**

The following data was not available or was not found:

- Not all the 'specific weights' of materials could be found. Certain materials like 'electronic facilities'. However, these materials are expected to have a low contribution to the result (kg$CO_2$/home);
- The planning (with the number of staff etc.) for the projects was not available;
- The information about the machinery used for the project was not available;
- Energy consumption from the factory was not available;
- For some materials, different densities were found. When this happened, either an average was calculated or the most frequently mentioned numbers were used.

**Assumptions Case C (transport & machinery)**

To fill the data gaps, the following assumptions have been made:

- Based on an interview with a work planner from a transportation company, an average distance of 90km was assumed;
- Supply concrete > 0km for transport to the factory since this is also excluded for other suppliers and the production of concrete has been done in the factory;
- Energy consumption and transport of staff is included, calculations based on the following assumptions:
    - Average working days of 260/year;
    - specific weights of materials;
    - average distance home > work;
    - Emissions car;
    - Emissions truck;
    - Gas and Electricity consumption of factory based on data and internet.
  - Days needed on the construction site (also for machinery) are assumed by a work planner from another construction firm since the ones from this firm did not have time for interviews;
  - Energy consumption machinery from the internet.
- Transport of machinery: is calculated for A5, not A3-MOD. This is due to not having enough knowledge about installations in the factory. also: it is calculated in the impact of the factory;
- The emissions/tkm are the same for industrial and traditional construction, this may differ in real life since industrial construction often has a full truck compared to traditional construction. In traditional construction, the perception is that subcontractors sometimes drive with one package instead of a full-loaded truck.

**Sensitivity analysis Case C (transport & machinery)**

Figure 2 presents the result of the sensitivity analysis conducted for input variables. The influence of those variables has been tested on the differences between the construction methods per $m^2$bvo in $kgCO_2$.

| Transport and machinery - Sensitivity analysis Case C (differences between construciton methods in kgCO2/m2bvo) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | unit | | 25% | 50% | 100% | 150% | 200% | |
| Distance to drive (materials) | km | 7% | 2.27 | 2.22 | 2.13 | 2.04 | 1.95 | -8% |
| Distance to drive (staff) | km | -54% | 0.97 | 1.36 | 2.13 | 2.9 | 3.68 | 73% |
| Distance to drive (machinery) | km | 161% | 5.55 | 4.41 | 2.13 | -0.15 | -2.43 | -214% |
| | | | | | | | | |
| Amount of employees in factory | empl. | 2% | 2.18 | 2.16 | 2.13 | 2.10 | 2.06 | -3% |
| Amount of working days | days/yr | -134% | -0.72 | 0.23 | 2.13 | 4.04 | 5.94 | 179% |
| Capacity factory | houses/yr | -21% | 1.69 | 1.98 | 2.13 | 2.18 | 2.20 | 3% |
| | | | | | | | | |
| Employees HBR | empl. | -137% | -0.78 | -0.06 | 2.13 | 4.07 | 6.01 | 182% |
| Crane HBR | units | -1171% | -22.82 | -14.51 | 2.13 | 18.77 | 35.4 | 1562% |
| Waste container HBR | units | -8% | 1.96 | 2.02 | 2.13 | 2.25 | 2.36 | 11% |
| Keet HBR | units | -8% | 1.96 | 2.02 | 2.13 | 2.25 | 2.36 | 11% |
| Steiger HBR | units | -2% | 2.08 | 2.10 | 2.13 | 2.16 | 2.20 | 3% |
| % TRD built IND | | -8% | 1.97 | 2.03 | 2.13 | 2.24 | 2.34 | 10% |
| | | | | | | | | |
| Days needed on construction site IND | days | 80% | 3.83 | 3.26 | 2.13 | 1.00 | -0.13 | -106% |
| Employees construction site industrial | Empl/house | 80% | 3.83 | 3.26 | 2.13 | 1.00 | -0.13 | -106% |
| Crane 2D-IND | units | 1333% | 30.53 | 21.06 | 2.13 | -16.80 | -35.73 | -1777% |
| Waste container IND | units | 2% | 2.18 | 2.16 | 2.13 | 2.10 | 2.07 | -3% |
| Keet IND | units | 5% | 2.23 | 2.20 | 2.13 | 2.07 | 2.00 | -6% |
| Steiger IND | units | 3% | 2.19 | 2.17 | 2.13 | 2.09 | 2.06 | -3% |
| | | | | | | | | |
| Gas usage factory (avg) | nm3 | 2% | 2.17 | 2.16 | 2.13 | 2.10 | 2.08 | -2% |
| Electricity usage factory (avg) | kWh | 1% | 2.15 | 2.14 | 2.13 | 2.12 | 2.10 | -1% |
| | | | | | | | | |
| Emissions/tkm >20t vrachtwagen | kgCO2/tkm | 1% | 2.15 | 2.14 | 2.13 | 2.12 | 2.10 | -1% |
| Emissions car staff (hybrid) | kgCO2/km | 15% | 2.44 | 2.34 | 2.13 | 1.93 | 1.72 | -19% |
| Emissions/nm3 gas | kgCO2/nm3 | -54% | 0.97 | 1.36 | 2.13 | 2.9 | 3.68 | 73% |
| Emissions/kWh Electricity (unknown) | kgCO2/kWh | 2% | 2.17 | 2.16 | 2.13 | 2.10 | 2.08 | -2% |
| Emissions/hour (crane) | kgCO2/hour | 1% | 2.15 | 2.14 | 2.13 | 2.12 | 2.10 | -1% |
| Emissions heavy transport + trailer | kgCO2/tkm | -9% | 1.93 | 2.00 | 2.13 | 2.26 | 2.39 | 12% |
| Emissions heavy transport - trailer | kgCO2/tkm | 162% | 5.58 | 4.43 | 2.13 | -0.17 | -2.47 | -216% |
| | | | | | | | | |
| Electricity usage/house 2D-IND | kWh | 274% | 7.96 | 6.02 | 2.13 | -1.76 | -5.64 | -365% |
| Electricity usage/house HBR | kWh | -489% | -8.28 | -4.81 | 2.13 | 9.07 | 16.01 | 652% |
| Working hours crane HBR | Hours | -177% | -1.65 | -0.39 | 2.13 | 4.65 | 7.17 | 237% |
| Working hours crane 2D-IND | Hours | 202% | 6.43 | 5.00 | 2.13 | -0.74 | -3.61 | -269% |

*Figure 2 The sensitivity analysis results for the variables used to calculate the impact of transport and machinery in Case C*

For all these input variables, a sensitivity analysis has been conducted on the differences in $kgCO_2$ per house. The results are shown in Figure 2.

The sensitivity analysis shows the following (from biggest to lowest impact):

- **Cranes used in 2D-IND:** the higher the number of cranes used in industrial construction, the bigger the differences between the construction methods in favour of hybrid construction;
- **Cranes used in HBR:** the higher the number of cranes used in hybrid construction, the bigger the differences between the construction methods in favour of industrial construction;

- **Electricity usage on construction site HBR:** the higher the electricity needed to construct a hybrid house, the bigger the differences between the construction methods in favour of industrial construction;
- **Electricity usage on construction site 2D-IND:** the higher the electricity needed to construct an industrial house, the bigger the differences between the construction methods in favour of hybrid construction;
- **Distance to drive (machinery):** the higher the distance to drive for the machinery, the bigger the difference between the construction methods in favour of hybrid construction;
- **Emissions heavy transport + trailer:** the higher this number, the bigger the difference in favour of hybrid construction;
- **Working hours crane HBR:** the higher the number, the bigger the difference in favour of industrial construction;
- **Working hours crane 2D-IND:** the higher the number, the bigger the difference in favour of hybrid construction.

Based on this analysis, it can be concluded that transporting and working the crane has a big impact on the result.

## 4. Impact of construction waste

This third model aims to calculate the $CO_2$ emissions belonging to construction waste for all three cases. First, the model calculated the $CO_2$ emissions belonging to transporting and processing traditional and industrial waste and second, the model calculated the possibly avoided $CO_2$ emissions.

**Data gaps in transporting and processing (construction waste)**

The following data was not available or was not found:

- Specific data on the amounts of construction waste arising for the different scenarios;
- Specific data on the distances from the projects to the waste processor.

**Assumptions transporting and processing (construction waste)**

To fill the data gaps, the following assumptions have been made:

- The amount of construction waste in the traditional cases is based on the average numbers of three different projects;
- The amount of construction waste in the industrial cases is based on the data from one factory;
- The amount of emissions emitted for transporting and processing the waste are based on an average of three different projects.

**Sensitivity analysis transporting and processing (construction waste)**

Figure 3 presents the result of the sensitivity analysis conducted for input variables. The influence of the following variables has been used for the sensitivity analysis:

- Total amount of waste (traditional);
- Total amount of waste (industrial);
- $kgCO_2/kg$ of construction waste for transporting and processing the waste.

The influence of those variables on the differences between the construction methods in $kgCO_2/m^2$bvo has been tested.

The following variables have the following influence on the differences between the construction methods in $kgCO_2/m^2$bvo (in order from biggest to lowest influence):

- **Traditional waste (total):** The higher this number, the bigger the differences between the construction methods in favour of industrial construction;
- **Emissions/kg waste:** The higher this number, the bigger the differences between the construction methods in favour of industrial construction;
- **Industrial waste (total):** The higher this number, the bigger the smaller the differences between the construction methods in favour of traditional construction.

| Transporting and processing construction waste - Sensitivity analysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 25% | 50% | 100% | 150% | 200% | | |
| Traditional waste (tot) | kg/m2 | -108% | -0.11 | 0.37 | 1.33 | 2.29 | 3.25 | 144% | kgCO2 |
| Industrial waste (total) | kg/m2 | 51% | 2.01 | 1.78 | 1.33 | 0.87 | 0.42 | -68% | kgCO2 |
| Emissions/kg waste | kgCO2/kg | -75% | 0.33 | 0.66 | 1.33 | 1.99 | 2.66 | 100% | kgCO2 |

*Figure 3 The sensitivity analysis results for the variables used to calculate the impact of transporting and processing construction waste*

Based on the results in Figure 3, it can be concluded that the biggest differences arise when the total amount of traditional construction changes. The influence of the amount of industrial waste is lower, since there is less waste coming from industrial construction. When the amount of construction waste for traditional construction could be reduced to 25%, this method emits fewer emissions than industrial construction.

The amount of $kgCO_2$/kg construction waste also has a certain influence. Meaning that when the process of transporting and processing the waste, was electrified, the differences will become smaller. This is an opportunity for traditional waste to reduce its environmental impact.

**Data gaps possible avoided emissions (construction waste)**

The following data was not available or was not found:

- The exact composition of the types of waste for the case studies used;
- The exact impact of producing certain types of construction waste.

**Assumptions possible avoided emissions (construction waste)**

To fill the data gaps, the following assumptions on compositions of types of waste have been made:

- **Industrial waste**: consisting of carton board and polyethylene;
- **Wood**: a bandwidth of 0.04 – 0.78 have been used, for producing softwood (low) **and** plywood (0.78);
- **Plastic**: consisting of polystyrene, PVC and PUR;
- **Paper and cardboard**: consists of carton board;
- **Debris**: consisting of clay brick and concrete;
- **Other**: consisting of steel and an average of all the other numbers;
- **Taken back by supplier**: insulation materials, assumed for polystyrene foam;
- **C&D**: an average of all numbers have been used.

**Sensitivity analysis possible avoided emissions (construction waste)**

Figure 4 presents the result of the sensitivity analysis conducted for input variables. The influence of the emissions/kg for producing a certain material has been used for the sensitivity analysis. The influence of those variables on the average amount of avoided emissions/$m^2$bvo has been tested.

| Avoided emissions - Sensitivity analysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 25% | 50% | 100% | 150% | 200% | | |
| Industrial waste | kgCO2/kg | 2% | 12.95 | 12.87 | 12.71 | 12.55 | 12.4 | -2% | kgCO2 |
| Wood (low) | kgCO2/kg | 0% | 12.65 | 12.67 | 12.71 | 12.75 | 12.79 | 1% | kgCO2 |
| Plastics | kgCO2/kg | 4% | 13.18 | 13.03 | 12.71 | 12.4 | 12.09 | -5% | kgCO2 |
| Paper and cardboard | kgCO2/kg | 0% | 12.77 | 12.75 | 12.71 | 12.68 | 12.65 | 0% | kgCO2 |
| Debris | kgCO2/kg | -13% | 11.04 | 11.6 | 12.71 | 13.83 | 14.94 | 18% | kgCO2 |
| C&D | kgCO2/kg | -97% | 0.38 | 4.49 | 12.71 | 20.93 | 29.15 | 129% | kgCO2 |
| Other | kgCO2/kg | 5% | 13.34 | 13.13 | 12.71 | 12.3 | 11.88 | -7% | kgCO2 |
| Taken back by supplier | kgCO2/kg | 25% | 15.86 | 14.81 | 12.71 | 10.62 | 8.53 | -33% | kgCO2 |

*Figure 4 The sensitivity analysis results for the variables used to calculate the impact of the avoided emissions*

The following variables have the following influence on the average amount of avoided emissions (in order from biggest to smallest influence). Impact of producing 1 kg of:

- **C&D:** The higher this number, the bigger the number of avoided emissions;
- **Taken back by supplier:** The lower this number, the bigger the number of avoided emissions;
- **Debris:** The higher this number, the bigger the number of avoided emissions;
- **Other:** The lower this number, the bigger the number of avoided emissions;
- **Plastics:** The lower this number, the bigger the number of avoided emissions;
- **Industrial waste:** The lower this number, the bigger the number of avoided emissions;
- **Wood (low):** The higher this number, the bigger the number of avoided emissions;
- **Paper and cardboard:** The influence of this variable is negligible.

Based on the results of this sensitivity analysis, the following conclusions can be drawn:

- Certain categories of waste result in more waste for industrial construction, this is due to more options to separate waste. That is why for some categories, a higher number of emissions results in a lower amount of avoided emissions;
- The more kg of waste, the higher the influence (C&D);
- The higher the number of emissions used to produce a certain material, the more influence (insulation).

## 5. Impact of the construction of the factory

The aim of the model created in Excel on this topic is to calculate the $CO_2$ emissions belonging to constructing a housing factory.

### Data gap housing factory

The following data was not available or was not found:

- There is no data to be found on the impact of constructing construction factories;
- There is little data to be found on the energy consumption of factories. However, this data is not scientific;
- There is limited data to be found about the area of the factory of Case B.

### Assumptions housing factory

To fill the data gaps, the following assumptions on compositions of types of waste have been made:

- Assumed is the impact of a construction factory/$m^2$. This assumption is based on the average impact of a: wooden board factory construction, a cement factory construction factory and a road vehicle factory. These numbers are originally from EcoInvent;
- Assumed is the area of the factory of Case B. Based on the information from Google Maps and their average annual production compared to the other factories, the assumption is that they are not finished yet with building the factory. Therefore assumed that 30% of the expected area is currently built;
- Assumed is an average lifespan of 50 years. This is based on data from EcoInvent.
- Assumed is the % of the traditional cases, built in the factory. This assumption is based on the share of the weight of the construction products compared to the total weight of the industrial constructed house.

### Sensitivity analysis housing factory

For the sensitivity analysis, the following actors have been used: the average impact in $CO_2/m^2$ of the factory, the area of the factory ($m^2$), the annual production of the factory (houses/year), the expected lifespan (years) and the percentage of the traditional case that has been constructed in the factory.

For every actor in every case, the percentages in the second row have been tested on the outcome: differences in $kgCO_2$/house. The column below 100% shows the original outcome.

| Factory - Sensitivity analysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Unit | | 25% | 50% | 100% | 150% | 200% | | |
| Average impact | kgCO2eq | 76% | -0.12 | -0.24 | -0.49 | -0.73 | -0.98 | -100% | kgCO2/m2 |
| Area | m2 | 76% | -0.12 | -0.24 | -0.49 | -0.73 | -0.98 | -100% | kgCO2/m2 |
| Annual production | houses/yr | -300% | -1.96 | -0.98 | -0.49 | -0.33 | -0.24 | 51% | kgCO2/m2 |
| Expected lifespan | yr | -300% | -1.96 | -0.98 | -0.49 | -0.33 | -0.24 | 51% | kgCO2/m2 |
| % industrial produced traditional | % | -53% | -0.75 | -0.66 | -0.49 | -0.32 | -0.14 | 71% | kgCO2/m2 |

*Figure 5 The sensitivity analysis results for the variables used to calculate the impact of the construction of the factory*

The following variables have the following influence on the average amount of differences between the construction methods in $kgCO_2/m^2$bvo:

- **Annual production of houses/year and expected lifespan:** the higher these numbers, the bigger the differences between the construction methods in favour of industrial construction;
- **Average impact and area:** the lower these numbers, the bigger the differences between the construction methods in favour of industrial construction;
- **% industrial produced:** the higher this number, the bigger the differences between the construction methods in favour of industrial construction.

Based on those observations, it can be concluded that high annual production and a longer lifespan can reduce the impact per $m^2$bvo. However, when a high impact or a large area is chosen, the impact will increase again.

## Appendix C – Issues with the MPG

**Different methods result in different values:** Dick van Ginkel mentions in a podcast that using different methods to calculate the MPG of the same house results in different values [10]. This should not be the case, since the construction method and the materialisation is the same.

**No monitoring:** the MPG is required by law in the Netherlands. However, additional to issue 2, different methods already result in different values, which also means that the value is influential and not consistent. As a result, tenders may go to the wrong parties.

There is also no monitoring on comparing the materialisation of the final house with the submitted materialisation on which the MPG is based. In reality, a house could be made of completely different materials.

**Higher impact due to new calculation method:** some Category-1 environmental profiles within the NMD are now calculated using the EN 15804+A2 rules instead of EN 15804+A1. Consequently, these materials or products have a heightened environmental impact compared to other Category 2 or 3 environmental profiles that still follow the EN 15804+A1 standards [7]. However, this problem should be solved after 2026, since environmental profiles expire after five years and from 2021 the new EN 15804+A2 should be maintained.

**Communication:** after five years, an environmental profile is no longer valid. As a result, these profiles were removed from the NMD. Most find this understandable, however the problem is that this happens without warning. So certain houses suddenly had an MPG that was a lot lower only because the environmental profiles were no longer available.

**Influences on the MPG:** a high MPG can result from factors such as a low bvo, an unfavourable architectural design (greater façade area) or an increased quantity of solar panelling to comply with NZEB regulations [12].

**Additional methods of computing environmental impact of buildings:** include BCI, NZEB, Embodied Carbon and $GWP_A$ (MPG-2). The publication of certain housing concepts and their performances also show that there are quite a few differences in these methods [13].