A COMPARATIVE LIFE CYCLE ASSESSMENT OF OFFSITE AND ONSITE CONSTRUCTION METHODS

P5

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09-01-2023

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Preface

Before you lies my thesis. It was written to finalize the master track Management in the Built Environment part of the master's program Architecture, Urbanism and Building Sciences. This report was written between September 2022 and January 2023. In this research I dug deeper into different types of offsite construction and measured their environmental impact.

Particularly, measuring the environmental impact turned out to be a difficult challenge in which I could really use some help. Fortunately, I was lucky enough to work on this research at Daiwa House Modular Europe surrounded by professionals driven to make the construction sector more sustainable. Their support has been very valuable, especially in understanding the MPG. I would love to thank them for their support.

Furthermore, I am grateful to my mentors Ad Straub and Hans Wamelink for their guidance during my graduation. By taking time out of their busy schedules to help me out is greatly appreciated. Their feedback and input has been very helpful.

Most importantly, I want to thank my family and friends. Their moral support throughout my studies have made my time in Delft bearable throughout the ups and downs.

I hope you enjoy reading this research!

Bryan Westerink

9th of January 2023, Den Haag

Summary

This research aimed to determine whether offsite construction leads to a lower environmental impact than onsite construction. Further, it is researched how the environmental impact of offsite construction can be reduced. This is of great importance as the construction industry has a significant environmental impact. Also, new buildings are becoming more and more energy efficient meaning that the construction phase of a building is taking an increasingly large share in the environmental impact of a building. Specifically, offsite construction is extra relevant as the Dutch government chooses to stimulate offsite construction methods for its lower environmental impact, speed and affordability.

In the first part of this research, relevant information about offsite construction methods and environmental impact assessments are researched by literature study. The environmental impact of 2D panelized and 3D volumetric construction is likely to differ as the amount of work offsite and transport logistics are different. Then, the MPG is selected as the method to assess the environmental impact. This tool measures the environmental impact of building materials throughout their lifetime. An MPG calculation is needed to obtain a building permit and cannot be higher than 0,80 EUR/GFA/Y for residential buildings. This tool was selected as these calculations are widely available for buildings.

Next, the differences between the following construction methods are compared and studied: onsite construction, modular offsite construction and panelized offsite construction. This is done through case studies of each of these construction methods. The case criteria were unit sizes of roughly 20 m^2, less than 5 years old and midrise height.

The cases were first compared on their differences in construction methods with a focus on differences in materials and processes. The research showed that offsite construction comes with extra steps in the construction stage, namely, assembling elements offsite and transporting them to the building site. Also, the end-of-life stages differ between onsite and offsite construction as the offsite cases could be dismantled and rebuilt whereas the onsite cases could only be demolished.

The cases were then compared on their environmental impact through the MPG calculations. The scope of the MPG was limited. Services and space plan (like kitchens and toilets) as described by Brand (1994) were left out of the assessment. Interior walls and doors however, were part of the assessment. To make sure the MPG's were reliable the MPG's used for the environmental impact The calculation showed that the environmental impact or the MPG was highest for the onsite case and lowest for the modular case. Offsite construction did come with a lower environmental impact than traditional construction in this study.

Afterward, recommendations were made to lower the environmental impact of offsite construction. Four strategies were identified after looking into the MPG comparison done in this research and in two other comparisons done by other researchers. The first two would also help to lower the environmental impact whereas the last two would only lead to a lower MPG:

To bring down the environmental impact:

1. Limiting the use of materials
2. Choosing different materials

To bring down the MPG score:

3. Use more cat 1 or 2 data
4. Enter a longer lifespan for a building

Subsequently, these 4 strategies are tested on their viability and effectiveness in the case of Leerpark Dordrecht. This was done by working on recommendations that were tested on their viability by interviewing one of the employees of Daiwa. When these recommendations were considered viable, they would be tested on their effectiveness by entering them into the MPG calculations.

Although strategy 1 was not feasible in this specific case, the other 3 cases proved viable and effective. These strategies would lead to a 29% reduction in the MPG compared to the MPG made earlier in this research.

However, there are limitations to the MPG when comparing the environmental impact of different buildings:

- The material-based approach does not allow to account for the design as a whole. Therefore it is impossible to take factors such as prefabrication or dismantling possibilities into account.
- The NMD is lacking data. There are not enough cat 1 or 2 items available in the NMD. When the specific product is not in the database category 3 data has to be chosen which is less accurate and comes with a multiplication factor of 1.3. This leads to different outcomes of the MPG when selecting elements of different makes even though the elements would be made from the same materials
- The energy performance of buildings is often enhanced by using building elements that negatively impact the MPG, like solar panels or insulation panels. As designers with a focus on sustainability often look into sustainable materials and low energy use the MPG often leads to a higher score than a building without specific sustainability goals.
- The MPG does not help lower construction emissions now as the embodied energy is spread over 75 years. Measuring the current carbon emissions would help to reduce carbon emissions now rather than in the long run with the current system. Further, it is hard to establish end-of-life scenarios for the future 75 years from now.
- Biobased materials are not fairly assessed in the current system. For example, the low energy needed to make these materials are not recognized in the current MPG as carbon sequestration is not measured. Therefore these materials get a worse score than one might expect.

Content

1 Introduction

1.1 Topic introduction

In 2018 the real estate and construction sector accounted for 36% of energy use and 39% of energy and process-related CO_2 emissions within Europe. Of these process-related CO_2 emissions, 11% came from construction and the manufacturing of building materials (Tavares et al., 2019). Furthermore, the goal of the Dutch government is to be 100% circular by 2050 (Rijksoverheid, 2016). Therefore, reducing the energy used to construct buildings is essential to reach climate goals.

Offsite construction, where building elements are produced in indoor environments outside the building site, is generally accepted as a solution to make the construction sector more environmentally sustainable (Ahn & Kim, 2014; Kamali & Hewage, 2016; Ministerie van Binnenlandse Zaken, 2021; Monahan & Powell, 2011; Tavares et al., 2019). To boost the production of more housing in the Netherlands the Dutch Ministry of the Interior and Kingdom Relations published a strategy to help the offsite construction industry increase its productivity. Not only for its faster housing production compared to onsite construction but also for its lower environmental impact. However, there is a lot of difference between the environmental impact of different offsite construction concepts for housing (Ministerie van Binnenlandse Zaken, 2021). In fact, some research even showed that offsite construction could even lead to a higher embodied energy in construction than traditional onsite construction (Teng et al., 2018). Therefore it is unclear how the environmental impact differs between offsite and onsite construction methods.

Furthermore, there are numerous different concepts within offsite construction. It is hard to compare these concepts directly to each other as they use different materials and assembly methods, possibly leading to very different environmental impacts. Several different typologies can be found in literature for offsite construction (Gibb, 2001; Ginigaddara et al., 2019; McKinsey, 2019). However, all these typologies have in common that they take the volumetric shape of the offsite produced elements into account which is either flat or volumetric. This shape could affect the efficiency of construction logistics. One of the contractors even claimed that its concept did not include the transport of air over the road suggesting that transporting volumetric units would be bad for the efficiency of construction logistics (Cobouw, n.d.). However, it is unclear how the different environmental impacts of offsite construction methods differ.

Lastly, as buildings are becoming increasingly energy efficient, emissions and energy used to construct new buildings are taking a more significant share in the total footprint of new buildings (Quale et al., 2012). Therefore decreasing the carbon footprint of construction is more important than ever. Especially for offsite construction in the Netherlands, since the government appointed this industry as the most crucial sector to decrease the environmental impact of the construction industry. This leads to the question:

How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products?

1.2 Problem statement

It is uncertain whether offsite construction methods perform better on environmental impact than traditional construction methods. Additionally, it is unclear how these offsite construction methods compare to each other looking at their environmental impact. Lastly, as the need is high to lower the environmental impact of construction it would be beneficial to figure out how this impact of offsite construction can be reduced.

1.3 Objectives

This research aims to give contractors working in offsite construction insight into how they can reach a lower environmental impact with their construction method. This will be relevant as the Dutch government is trying to adopt strategies to lower emissions from the construction sector by reducing the required MPG values (Ministerie van Binnenlandse Zaken, 2021). The MPG measures the environmental impact of building materials throughout their lifetime. Also, this research will provide these contractors with a better insight into the performance of their products giving opportunities to develop their products further to lower their environmental impact. Furthermore, the research will be valuable for the scientific field as it adds to the knowledge about LCA performance of offsite construction in the Dutch context compared to onsite construction. Lastly, this research will lead to further research into sub-phases in an LCA assessment such as differences in the efficiency of transport of different construction methods and its effect on the environmental impact.

1.4 Research questions

Main research question: *How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products?*

This question will be answered using the following sub-questions:

1. What are the different typologies within offsite construction?
2. How can the environmental impact of buildings be measured?
3. What are the differences between offsite and onsite construction regarding construction processes and used materials?
4. How does the environmental impact differ between offsite and onsite construction methods?
5. What are the limitations of the MPG in comparing different construction methods?

1.5 Methodology

This research was conducted using a mixed methods approach. Whereby the research was structured into different parts, see Table 1 Research outline.

Analysis	Chapter 2: Typologies within offsite construction	What are the different typologies within offsite construction?	Literature study
	Chapter 3: Measuring environmental impact	How can the environmental impact of buildings be measured?	Literature study
Assessment	Chapter 4: Differences in construction methods	What are the differences between offsite and onsite construction regarding construction processes and materials?	Case study
	Chapter 5: Environmental impact comparison	How does the environmental impact differ between offsite and onsite construction methods?	Case study
Recommendations	Chapter 6: Towards a lower MPG	How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products?	Literature study
	Chapter 7: Daiwa towards a 25% lower MPG	What are the possibilities for Daiwa Modular House Europe to reduce the environmental impact of their project Leerpark Dordrecht by 25%?	Case study + interviews
Limitations	Chapter 8: Limitations of the MPG	What are the limitations of the MPG in comparing different construction methods?	Literature study+ case study + interviews

Table 1 Research outline

1.5.1 Analysis

The first two chapters analyze essential topics for the rest of the research. These analyses form the basis for the rest of the study.

1.5.1.1 Chapter 2

First, through literature study, an analysis was made of the different types of offsite construction. This led to a selection of typologies of offsite construction that could be compared on their environmental impact to traditional construction. This was necessary as the introduction indicated that the different types of offsite construction could lead to different environmental impacts. Multiple sources were used to enhance the reliability of the findings.

1.5.1.2 Chapter 3

Then a tool was searched to measure the environmental impact of buildings through literature study. By first looking into broader environmental assessments and filtering to more specific tools used in the Netherlands a broad insight was created into the possibilities. The right tool for the scope of this research was found by researching different tools and seeing whether this would be achievable within the time frame planned for this research. Finally, the completeness of the literature study was ensured by looking both into environmental assessments like those used in the scientific field and trying to find tools used in practice.

1.5.2 Assessment

1.5.2.1 Chapter 4

For the assessment, the first step was to look into the differences between the construction methods that are relevant for the environmental impact assessment. This is done with case studies, three construction projects were used as cases. All three of the cases are built with different construction methods. This is further explained in 1.6.

1.5.2.2 Chapter 5

Then the environmental impact of each of the cases is measured using the tool identified in chapter 3. This chapter shows how the environmental impact differs between the cases. This chapter also tests whether the differences between the construction methods found in chapter 4 are considered in the environmental impact assessment. This shows the limitations of the tool that was used.

1.5.3 Recommendations

1.5.3.1 Chapter 6

In this part of the research recommendations are made for offsite construction contractors to lower their environmental impact. This is done by analyzing the comparison of chapter 5 and seeing whether there would be options to lower the environmental impact. Also, a literature study is conducted to see whether other options are available. This leads to a number of strategies to reduce the environmental impact.

1.5.3.2 Chapter 7

These strategies are tested on their viability and effectiveness through a case study. To test the viability, the identified strategies are converted into recommendations for a specific case and discussed in semi-structured interviews. The interviewee had a lot of background knowledge of the construction method and engineering process of the contractor of this case. This made it possible to ask whether using these strategies would be doable for that party. Then the effectiveness of the recommendations were tested by entering the alternatives into the environmental impact assessment tool. By using multiple research methods in this part the recommendations were not just strategies from literature but feasible options that were proven to be viable in the interviews and effective through the environmental impact calculation.

1.5.4 Limitations

1.5.4.1 Chapter 8

Limitations found in chapter 5 are explained here. Other limitations were sourced from literature. Then, semi-structured interviews were conducted to find whether there were more limitations and to validate the already-seen limitations. The interviewees work at companies that either research the environmental impact assessment or use these environmental impact assessments daily. Therefore, the specific professionals are all very familiar with the impact assessment.

1.6 Case study

This study focuses on medium high-rise buildings with a unit size of roughly 20 m^2 with repetitiveness in the layout.

A unit size of roughly 20 m^2 was a selection criterion, as these units can be easily converted into studio apartments, often used for student housing. This type of housing is extra relevant as the Netherlands is facing a shortage in student housing. This shortage is expected to grow to 26.000 units in 2026 (Savills, 2021), which means that it is well possible that a lot of student housing will be built in the coming years. Importantly, student housing will not be a selection criterion for the cases but the unit size is.

The repetitiveness in the layout is chosen as modular construction is most efficient in buildings with a lot of repetition in the layout (ABN Amro, 2019). Nonetheless, the availability of cases has shown that the other construction methods are also viable for these housing types. To foster comparability the three cases were new or <5 years old but did obtain a building permit. This proved the feasibility of the construction methods.

The following factors were taken into account for the comparison as these are relevant for comparability, most measures are in line with the design parameters identified by Stichting Nationale Milieudatabase (2020) that affect the MPG score the most. However, thermal performance of the skin of the building was added as thermal insulation has a significant environmental impact (Grover, 2020).

- Gross Floor area
- Number of stories
- Façade area
- Open façade areas
- Thermal performance

1.7 Scope

An essential part of this research is an LCA in line with the MPG. This means the 19 impact categories are considered as required as of 1 January 2022. The default building life is 75 years as the standard for residential buildings (Stichting Nationale Milieudatabase, 2020). However, as the primary purpose of this analysis will be to compare construction methods the services and spaceplan in line with Brand (1994) are left out of the assessment. Interior walls and doors however are part of the assessment as these are different for each construction method. The unit of the end result will be presented in €/GFA, in line with MPG guidelines. This allows taking multiple impact categories into account in one unit. Only elements within the building are considered and inventory is left out of the assessment.

Further, this research is focused on construction methods. Contractors can choose between different construction methods. Large contractor BAM, for example utilizes different offsite and onsite construction methods in their various projects. In this research, contractors are considered to be the party that utilizes a construction method to deliver a building. This research will look into the later parts of the whole supply chain in construction. Upstream suppliers are not subjected to the research question. In this research, all construction methods are set up and utilized by the contractors. On the other hand, suppliers are identified as the parties who supply materials or sub-elements to the contractors. The construction method used in this research is either 2D panelized offsite, 3D volumetric offsite or onsite construction. This restriction is only affected by the shape of the offsite-produced elements and not by material choice.

2 Typologies within offsite construction

The aim of this chapter is to answer the following research question:

What are the different typologies within offsite construction?

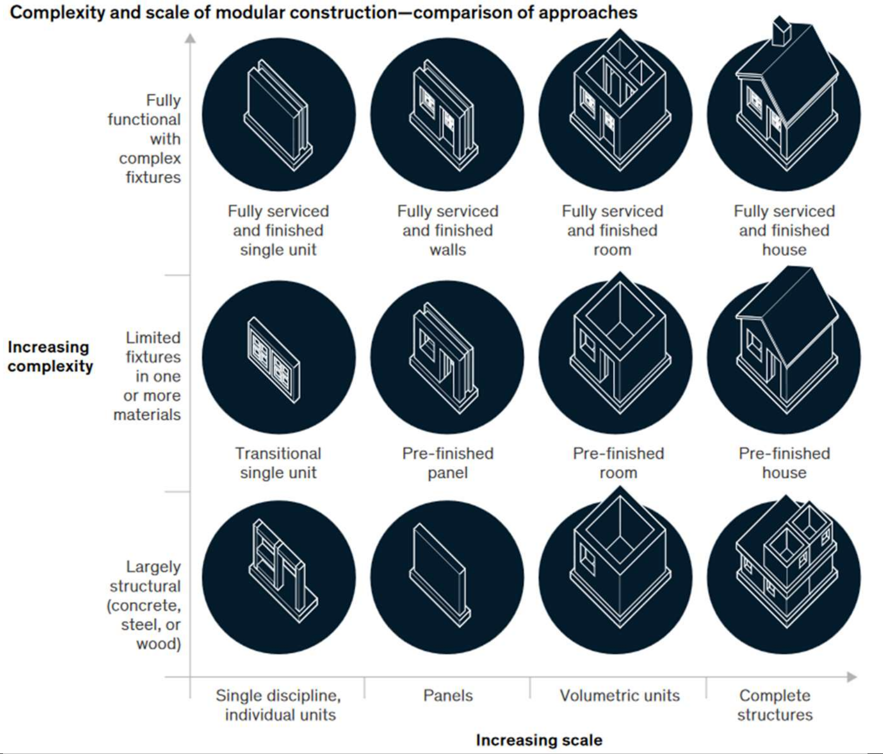
To answer this question literature will be reviewed. In addition, frameworks and typologies are presented to distinguish the different types of offsite construction.

2.1 Offsite construction typologies

There seems to be discussion in the scientific field about different typologies of offsite construction (Ayinla et al., 2019; Ginigaddara et al., 2019; Jonsson & Rudberg, 2014). Gibb worked on his classification in line with prior research and identified four types: component manufacture and sub-assembly, non-volumetric pre-assembly, volumetric pre-assembly and modular units (Gibb, 2001). According to Ginigaddara et al. (2019) several later classifications are based on Gibb's work. Jonsson and Rudberg (2014) recognized the discussion within the field and assessed the types identified by Gibb on standardization and degree of offsite production (Jonsson & Rudberg, 2014). Conversely, Ayinla et al. (2019) analyzed the literature on offsite construction methods, showed many misconceptions about the classification of offsite construction, and proved that 18 references all used different classifications (Ayinla et al., 2019). Ginigaddara et al. (2019) also showed that there are a lot of misconceptions and proposed to use: components, panels, pods, modules, complete building and flat pack. Real estate consultant McKinsey (2019) also drafted a classification system taking the scale and complexity into account leading to 12 different classifications. The different classifications are shown in Table 2.

Table 2 Classifications of offsite construction methods in literature

Gibb, 2001	Component manufacture and sub-assembly	Small scale sub-assembly of construction project components	Light fitting, windows
	Non-volumetric pre-assembly	Two dimensional building components produced offsite	Walls, prepared segments pipe fittings
	Volumetric pre-assembly	Components that encompass a usable space	Toilet pods, elevator shafts
	Modular units	Components that form the building itself also structurally	Office blocks, multi-story residential blocks
Ginigaddara et al., 2019	Components	10-15% of project value and need fitting on site	Light fitting, windows
	Panels	15-25% of project value and do not enclose a space	Walls, roofs

	Pods	Non-structural volumetric part of the building	Toilet pods, bathroom pods
	Modules	Structural volumetric part of the building	Stackable offices, stackable residential units
	Complete building	Building with significant offsite skills and extremely minimal amount of onsite skills	
	Flat pack	Construction method where onsite skills are irrelevant	
McKinsey, 2019	**Complexity and scale of modular construction—comparison of approaches** 		

The different typologies all take the shape of the prefabricated elements into account. This is either panelized 2D elements or volumetric 3D modules. Each type has its pros and cons. Smaller prefabricated elements like 2D elements allow for more customization and custom solutions onsite. However, as these element need more work onsite these methods make less use of the benefits of offsite construction. 3D modular construction on the other hand works with more offsite man hours enabling maximal time and resource efficiency. However, modular construction is constrained by transport limitations. The maximum width for road transport is often 3.5 meters (McKinsey, 2019). Further, people assume that the transport of 2D panels would be more efficient than that of modules.

A contractor of panelized construction even claimed that his product is easier to transport as he does not transport air over the road (Cobouw, n.d.). Lopez and Froese (2016) showed however that the differences in cost-effectiveness of the transport of both construction methods only marginally differ. On the other hand, Rezzag Lebza (2022) research showed that the emissions from transport are lower for modular timber construction compared to panelized timber construction. This shows that there is unclairity about the difference in environmental impact between 2D and 3D offsite construction.

2.2 Conclusion

This chapter answers the following question:

What are the different typologies within offsite construction?

Research is not conclusive on typologies within offsite construction. They use different approaches to create distinctions and contradict one another in various fields. The one thing they do have in common is that different typologies all take the shape of the offsite-produced elements into account. This is either panelized 2D elements or volumetric 3D modules. These different typologies work with a different balance in onsite and offsite working hours. Also, the transportation is very different. This will affect the environmental impacts of the construction methods. Therefore, these two types of offsite construction methods will be compared on their environmental impact in this research.

However, it is relevant first to identify the right tool to measure the environmental impact in the next chapter.

3 Measuring environmental impact

The aim of this chapter is to answer the following question:

How can the environmental impact of buildings be measured?

The literature study presents different methods to measure the environmental impact of construction. First, the more general forms of life cycle assessments (LCA) are given. Then, towards the end of this chapter the Dutch system based on the LCA will be presented including its scope.

3.1 Life Cycle Assessment (LCA)

Embodied energy is the energy needed to produce materials. Depending on the kind of assessment, different stages in the lifecycle of materials can be taken into account (Abey & Anand, 2019; Monahan & Powell, 2011). Although a significant part of the carbon footprint of a building is a result of the use stage of a building, the construction phase also has a substantial impact on the footprint. Often the emissions from the construction phase are comparable to those from using the building for a few years. However, buildings are becoming more and more energy efficient making the construction phase of the building more important for the carbon footprint of a building (Monahan & Powell, 2011).

There are different methods to assess embodied energy but the most predominant ones in research are life cycle assessment (LCA) based methodologies (Monahan & Powell, 2011). The LCA measures the environmental impact of a product throughout different stages of a product's life. It has a fixed structure and is connected to ISO 14040 (Muralikrishna & Manickam, 2017). Different stages can be taken into account. For example, a cradle-to-gate assessment will only consider the environmental impact of production from raw materials. Cradle-to-grave comes with the impact of the use stage, and cradle-to-cradle will take the impact into account of recycling the product, see Figure 1.

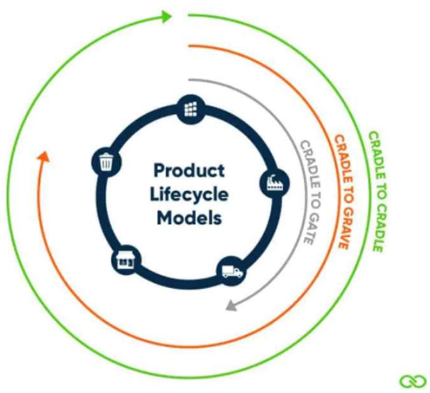


Figure 1 LCA stages (Ecochain, 2019a)

The LCA scope covers different construction stages prescribed by NEN-EN 15978 guidelines, as shown in Figure 2 LCA stages following NEN-EN 15978 (Joint Research Centre (European Commission) et al., 2018). The A-stages look into the stages of construction and transport of materials. The B-stages look into the operational stage of a building including the energy use and maintenance. The C-stages look into energy and emissions from the disposal and demolition of the building. Finally, the D-stage looks into reuse, recycling or recovery. This is especially important for objects that can have multiple lifecycles. (Institution of Structural Engineers (Great Britain), 2020; Joint Research Centre (European Commission) et al., 2018; Muralikrishna & Manickam, 2017).

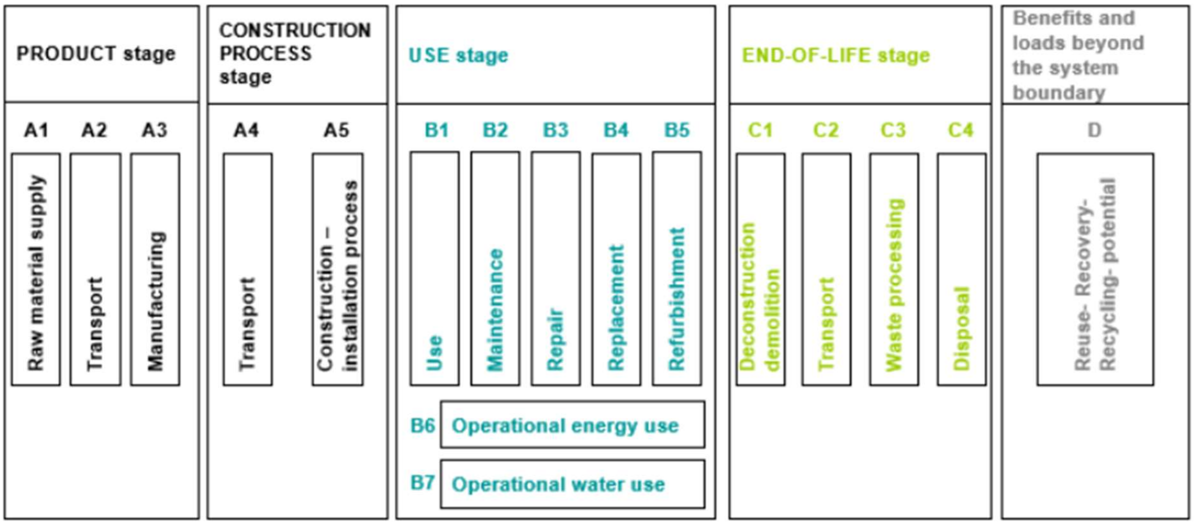


Figure 2 LCA stages following NEN-EN 15978 (Joint Research Centre (European Commission) et al., 2018)

The NEN-EN 15978 prescribes different impact categories which can be affected by the whole process. This can be relevant as other production processes can affect the environment differently. A selection of impact categories used for NEN EN15804 + A2 is shown in Table 3. Global Warming Potential is most often used and prescribes greenhouse gas emissions. This is for example the indicator used for the LCA within Europe's Levels framework to assess the environmental impact of real estate (Dodd et al., 2021; Muralikrishna & Manickam, 2017).

Table 3: Impact categories in line with EN15804 + A2 (Ecochain, 2019b)

Impact category / Indicator	Unit
Climate change – total	kg CO_2-eq
Climate change – fossil	kg CO_2-eq
Climate change – biogenic	kg CO_2-eq
Climate change – land use	kg CO_2-eq
Ozone depletion	kg CFC-11-eq
Acidification	kg mol H+
Eutrophication – freshwater	kg PO_4-eq
Eutrophication – marine	Kg N-eq
Eutrophication – terrestrial	mol N-eq
Photochemical ozone formation	kg NMVOC-eq
Depletion of abiotic resources – minerals and metals	kg Sb-eq
Depletion of abiotic resources – fossil fuels	MJ, net calorific value
Human toxicity – cancer, non-cancer	CTUh
Eco-toxicity (freshwater)	CTUe
Water use	m3 world eq. deprived
Land use	Dimensionless
Ionising radiation, human health	kBq U-235
Particulate matter emissions	Disease incidence

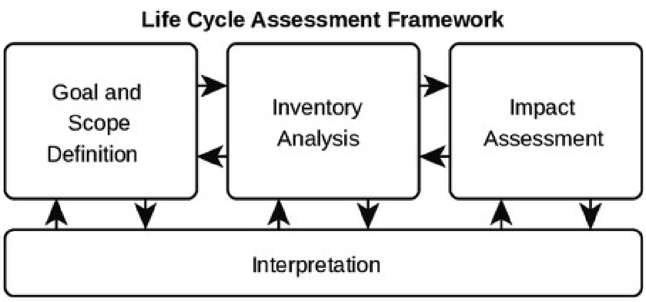


Figure 3: Steps of the LCA in line with ISO14040 (Lamperti Tornaghi et al., 2018)

The LCA has a fixed order of four steps in ISO14040, shown in Figure 3. Each step will be discussed in order:

3.1.1 Step 1: Goal and scope

In the first step the goal and aim of the assessment are determined. This will influence the stages that will be taken into account and the research's depth.

3.1.2 Step 2: Life Cycle Inventory

This step maps the flow of materials and energy throughout the process. In other words, inputs and outputs of the process will be mapped, like the input of raw materials like steel and the output of emissions during the transport of steel.

3.1.3 Step 3: Life Cycle Impact Assessment

After mapping the inputs and outputs this step will assess the impact on the environment of each of these. There are numerous different impact categories available within EN 15978 but the most common one is the Global Warming Potential (GWP).

3.1.4 Step 4: Interpretation

After mapping out the impacts, the last step is interpreting the results and potentially shaping recommendations or conclusions. Also, this step comes with a thorough assessment of the credibility of the rest of the LCA (Ecochain, 2019a; Grover, 2020; Muralikrishna & Manickam, 2017).

3.2 Tools to perform LCA's

Different tools have been developed to help assess the LCA performance of buildings. Tools rely on manually entered data about the building for the second step. This is coupled to publicly available Environmental Product Declarations (EPD) in which suppliers have already calculated their products' LCA performance. In these EPD's also other data is given to see how the performance is calculated. By combining the quantities of different materials used in a building and the LCA performance of products per unit, tools can quickly calculate LCA performance of a building based on its design. Most tools already integrated publicly available EPD's, making step 2, life cycle inventory, a lot easier (Dodd et al., 2021; Hollberg & Ruth, 2016).

3.3 Milieuprestatie Gebouwen (MPG)

Milieuprestatie Gebouwen (MPG) is a Dutch system to indicate the environmental impact of materials used in new office and residential buildings. An MPG calculation is a prerequisite to obtain a building permit as of 2018 for buildings larger than 100 m^2 GFA. This is enforced in the Dutch building decree. This calculation has to be done in line with the guidelines determined by the Nationale MilieuDatabase (NMD) (Rijksdienst voor Ondernemend Nederland, 2021). With this calculation it is possible to calculate the materials' environmental performance during its lifecycle within buildings and compare this to other buildings (Stichting Nationale Milieudatabase, 2022)

With this system, the Netherlands is one of the front runners in measuring environmental performance in all stages. Other European countries, however are also working on similar systems. France will implement a system in 2022, Finland in 2025, Denmark in 2023 and Sweden in 2022. However, these systems use slightly different units for the calculation and are often without a maximum value (BPIE (Buildings Performance Institute Europe), 2022; OneClick LCA, 2022).

The MPG is based on the guidelines of the LCA described in EN15978. However, it is slightly adapted to the Dutch system. These adaptations made it possible to work with predefined scenarios and fixed values. Also, the use of generic data (proprietary data) if no producer- or branch-specific data are available is allowed in this assessment. This resulted in EN15804 which can only be applied to buildings as opposed to EN15978 which is also suited for infrastructure projects (Stichting Nationale Milieudatabase, 2022).

When performing an MPG calculation data from the individual building elements and processes have to be selected from the ''Nationale Milieu Database''. Stichting National Milieudatabase manages this database. Producers and suppliers can ensure their product is in the database by submitting LCA calculations via an external advisor. However, not all producers do this. To make sure all buildings can still be entered into the system three categories of data are available:

- Category 1: Brand-specific data from suppliers
- Category 2: Industry-specific data
- Category 3: Unverified data supplied by NMD with a multiplication factor of 130%

In the assessment of building elements, 19 impact categories are considered. However, not all of these categories have the same importance and their impact on the calculations differs. All these categories are translated into shadow price costs (schaduwkosten), see Table 4. The idea is to put the often unknown values of the impact categories into more recognizable Euros, see Figure 4. After assessing this value for 75 years for residential units and 50 years for offices, the value will be divided by the Gross Floor Area (GFA) of the building resulting in a value expressed in Euros per year per GFA, see formula underneath (Stichting Nationale Milieudatabase, 2022).

$$MPG = \frac{Sum\ shadow\ costs\ of\ materials}{lifespan\ building\ *\ GFA}$$

Milieu-impactcategorie	Equivalent eenheid	Weegfactor [€ / kg equivalent]
Uitputting abiotische grondstoffen (exclusief fossiele energiedragers) – ADP	Sb eq	€ 0,16
Uitputting fossiele energiedragers – ADP	Sb eq[10]	€ 0,16
Klimaatsverandering – GWP 100 j.	CO_2 eq	€ 0,05
Aantasting ozonlaag – ODP	CFK-11 eq	€ 30
Fotochemische oxidantvorming – POCP	C_2H_4 eq	€ 2
Verzuring – AP	SO_2 eq	€ 4
Vermesting – EP	PO_4 eq	€ 9
Humane toxiciteit – HTP	1,4-DCB eq	€ 0,09
Zoetwater aquatische ecotoxiciteit – FAETP	1,4-DCB eq	€ 0,03
Mariene aquatische ecotoxiciteit - MAETP	1,4-DCB eq	€ 0,0001
Terrestrische ecotoxiciteit – TETP	1,4-DCB eq	€ 0,06

Table 4 Shadow costs for various impact categories(Hillege, 2019)

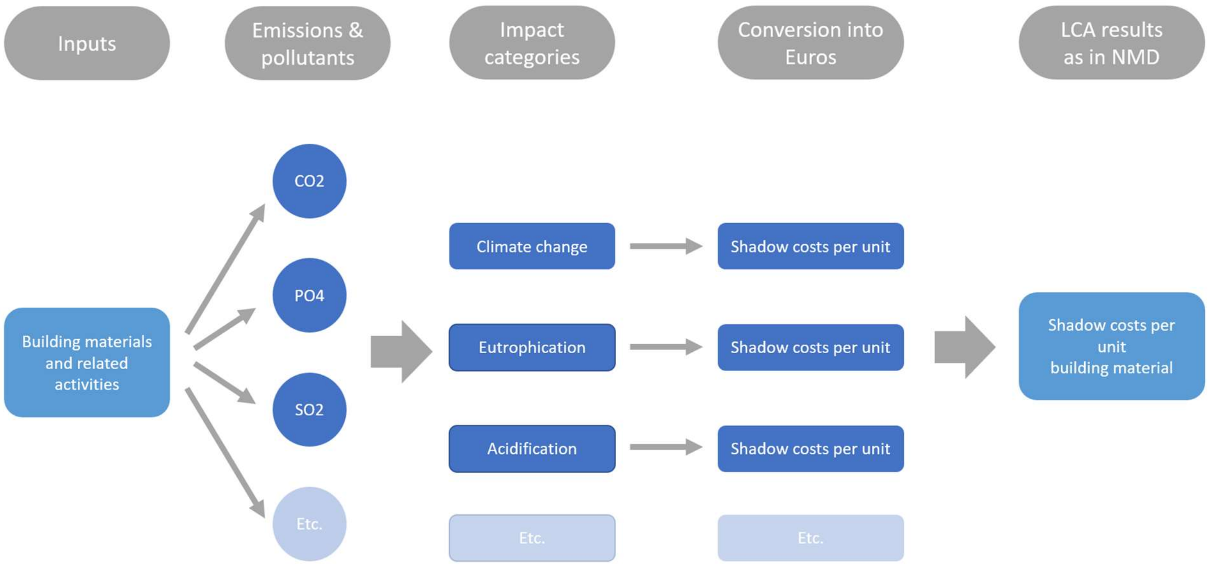


Figure 4 Process for LCA's in NMD (own work based on(Hillege, 2019))

As the process for calculating each MPG has to be uniform, Stichting Nationale Milieudatabase made guidelines. The scope is determined to be a cradle-to-cradle assessment of all materials used in the building. However, phases B5: Refurbishment, B6: Operational energy use and B7: Operational water use are left out of the calculation. As a result, the MPG only considers the building materials' impact and not the building's energetic performance, see Table 5.

In 2021, the maximum value was set at 0,8 €/Y/GFA for residential buildings. In the future this value will be reduced to 0,5 €/Y/GFA in 2030 (Rijksdienst voor Ondernemend Nederland, 2021). In practice, however, introducing this system did not lead to significant reductions as most building methods comply with this value without iterations even after the decrease to 0,8 (Bijlsma, 2022).

Product stage	Construction process stage	Use stage	End of life stage	Benefits and loads beyond system boundary
A*1: Raw material supply* A2: Transport A3: Manufacturing	A4: Transport A5: Construction installation process	B1: Use B2: Maintenance B3: Repair B4: Replacement ~~B5: Refurbishment~~ ~~B6: Energy use~~ ~~B7: Water use~~	C1: Deconstruction C2: Transport C3: Waste processing C4: Disposal	D: Reuse, recovery and recycling potential

Table 5 LIfe cycle stages with stages included in MPG (own work based on NEN (2019))

3.3.1 Most important factors in MPG

Installations, facades and floors are the building elements that affect the MPG score the most. This stems from the fact that installations are often complex systems with many parts that cost a lot of input to produce and maintain. Facades and floors on the other hand are often physically the most significant part of a building and are as a result important for the MPG score, see Table 6 (Stichting Nationale Milieudatabase, 2020).

Foundation	7%
Floors	16%
Structural elements	7%
Facades	18%
Roofs	6%
Installations	33%
Interior elements	13%

Table 6 Share building elements in MPG of residential buildings (Stichting Nationale Milieudatabase, 2020)

Stichting Nationale Milieudatabase (2020) also researched the five most impactful design parameters in buildings that affect the MPG value.

1. Gross Floor Area:

The MPG is often lower for larger buildings as these buildings often share facilities and entrance areas for a larger floor area. Therefore smaller ones often score relatively high.

2. Number of stories:

The MPG for relatively low residential buildings tends to be high as traffic areas can only be used for a limited number of units. However, very high buildings also have a high score due to the heavy construction needed.

3. Story height:
The façade has a significant influence on the total MPG. High stories therefore lead to a high MPG.

4. Façade surface area:
The façade has a significant influence on the total MPG. Buildings with a high façade to floor ratio score worse on the MPG.

5. Open façade areas:
Glass has a relatively high environmental impact. Buildings with large openings in the façade would therefore score higher on MPG.

3.4 Alternatives for MPG

There are alternatives for the MPG to measure the resource efficiency of buildings also used in the Netherlands. However, these assessment methods are not required within the Dutch building decree as opposed to the MPG.

3.4.1 Het Nieuwe Normaal

Het Nieuwe Normaal (HNN) Dutch for The New Normal is working towards a new standard and common performance indicators for circular construction. The project was initiated by Cirkelstad, an organization connecting public and private parties focusing on circularity in the built environment and the Dutch ministry of national affairs. HNN will be presented in 2023 and is developed up until then based on field projects, with project evaluations from both participating partners and others. HNN is constantly seeking new relevant indicators to include in their new standard. Those indicators have been included in draft versions (0.1, 0.2, etc), which have been widely shared.

In

Table 7 all indicators from the HNN concerning materials are shown including the most important question for each indicator. The table shows that HNN is very elaborate and does take the MPG into account but goes beyond this by adding extra indicators. However, there has not been a suitable tool to measure each of these indicators yet but this should be fixed when the final HNN will be presented in 2023 (Cirkelstad, 2022; W. Kuijper, personal communication, October 24, 2022).

Table 7 Indicators in HNN concerning materials and most important question

Handling residual materials (demolition)	What portion of the waste material from (partial) demolition will be reused, recycled to a high quality, landfilled and combusted?
Handling residual materials(construction)	What measures were taken to avoid residual material during construction where possible? And: What is the amount of residual material during construction, and what proportion of this is reused or high-grade recycled?
Environmental impact	What is the environmental performance (MPG) value of the building?
Construction Stored Carbon	What is the Construction Stored Carbon (CSC) of the building?
Use of materials	What is the proportion of renewable, reused, recycled and virgin material per system layer?
Reuse potential	What is the reuse potential of the materials used, per system layer?
Possibilities for dismantling	What is the degree of demount ability of the different layers of the building?
Layout flexibility	What is the degree of layout flexibility of the building?
Toxicity	How many products in the building are certified, based on Living Building Challenge's Red List (v. 4.0), Material Health Certificate (based on Cradle2Cradle) or a REACH certificate?

3.4.2 Building Circularity Index

The BCI measurement method was developed to guide circularity early in the design process. The final score is expressed as a percentage between 0% and 100%, where 0% is fully linear and 100% is fully circular. To assess the BCI two vital indicators are: material use and possibilities for dismantling. This is different from the other tools have a broader scope for evaluating sustainability.

The material circularity index (MCI) is calculated first to assess the BCI. This indicator considers the sourcing of materials, the waste processing at the end of a product's life, and the lifespan of materials. The scope of this MCI is limited to one single material or part.

Also, the demount ability of a material is calculated when a material is fixed in a building. This is assessed by considering the type of connection, accessibility of connection, form enclosure and intersections.

The MCI and the Detachability Index make up the Product Circularity Index . The Product Circularity Index represents the circular potential of a product when installed in a building structure. A building consists out of different products and adding all the Product Circularity Index's up leads to the total BCI (BCI GEBOUW, n.d.).

In contrast to the MPG, this method considers elements separately instead of solely assessing the materials. This can prove to be a valuable difference in recycling a building.

However, this tool is not widely used and not available for many buildings. Also, using this method will be too time-consuming for this research.

3.4.3 BREEAM

BREEAM is an environmental assessment method for a sustainable built environment. Within BREEAM, projects are assessed on their sustainability by measuring varying aspects of sustainability from the sustainability of materials up to the management of the building project. BREEAM was initially developed by the Building Research Establishment (BRE). Dutch Green Building Council made the method compatible with the Dutch situation.

One of the categories assessed for BREEAM is materials. The indicators for this category are shown underneath in Table 8. The first indicator already assesses whether the MPG is under the value for reference buildings while other indicators go even further to measure the environmental impact of the building.

Compared to the MPG this tool is much broader and has a lot of indicators. However, BREEAM can only be used by qualified people and would not be feasible with this research period.

Table 8 Indicators materials Breeam

MAT 01	Environmental impact of building materials
MAT 03	Responsible sourcing of building materials
MAT 05	Robustness of building materials
MAT 06	Material efficiency
MAT 07	Detachability

3.4.4 GPR gebouw

GPR gebouw is an environmental assessment method developed by W/E Adviseurs in 1995 which was constantly updated to the current day. In this tool sustainability is mapped through report ratings for the themes: energy, environment, health, use quality and future value. The main goal of this tool is to give insight into the sustainability of buildings and give a common ground to discuss this (GPR Gebouw, n.d.).

Resource efficiency is assessed within the theme environment. The following aspects are mapped:

- MPG value
- Reuse of materials (input)
- Circular materials (biobased)
- Wood from sustainably managed forests
- Detachability
- Reuse potential materials (output)

GPR gebouw is more extensive than the MPG alone. In fact, the MPG is even part of this assessment.

Just like BREEAM this tool is broad and has a lot of indicators. Also, GPR gebouw can only be used by qualified people and exceeds the resources for this research.

3.5 Conclusion

The aim of this chapter is to answer the following question:

How can the environmental impact of buildings be measured?

The environmental impact of a building can be measured with a life cycle assessment. Life cycle assessments are a known method to measure the environmental impact of a product like a building. The Netherlands uses a variant of the LCA, the MPG for measuring the resource efficiency of buildings in the Netherlands. There are alternatives for this method but these are not broadly available for existing buildings, are not limited to embodied energy or the researcher is not qualified to make such an assessment, see Table 9. Therefore, the MPG will be used in the rest of this research.

	Measures embodied energy	Researcher is qualified to do this assessment	Broadly available for existing buildings (projects)	Limited to embodied energy
MPG	X	X	X	X
HNN	X	X		
BCI	X	X		X
BREEAM	X			
GPR	X			

Table 9 Assessment of tools to measure embodied energy

This chapter shows that building materials and phasing are important for LCA and MPG calculations. These two characteristics are therefore assessed in the following chapter.

4 Differences between construction methods

4.1 Introduction

This chapter explains the differences in phasing and materials between the construction methods discussed in chapter 2. To answer the following question:

What are the differences between offsite and onsite construction regarding construction processes and materials?

Differences in phasing and materials are discussed further as the phasing is relevant mainly for the LCA calculations. In contrast, the materials are very relevant for MPG calculations as presented in the last chapter. Planning and materials will be researched by examining case studies of realized buildings and highlighting the differences. The LCA product stages will be used as a framework to show stages' differences, whereas the materials' differences will be shown in tables.

4.1.1 Case study criteria

Chapter 3 showed that the two types of offsite construction work with different logistics between the offsite production location and the building site. Therefore, it is necessary to test both offsite construction methods' sustainability as these two concepts might have different environmental impacts. Both methods will be compared to a traditional case to test whether offsite construction is more sustainable.

As explained in the introduction, the focus will be on medium high-rise buildings (4 – 10 floors) with a unit size of roughly 20 m^2. As the environmental impact is affected by choice of materials, cases were selected with different building materials. This is also relevant as many offsite construction methods are available in various materials. Furthermore, the cases were not older than five years to ensure that there were no outdated construction methods. Repetitiveness within the building's layout would be beneficial for the cases as this is often the case in modular buildings as well and will lead to better comparability (ABN Amro, 2019).

4.2 LCA product stages

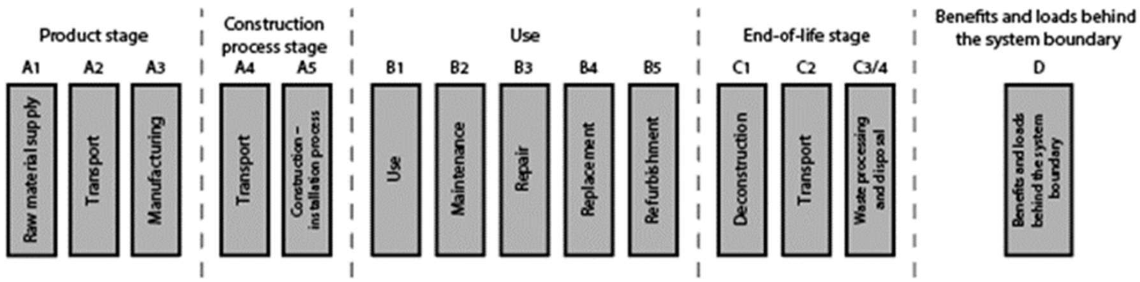


Figure 5 LCA stages following NEN-EN 15804 (own work)

The LCA works with distinct lifecycle stages described in NEN-EN 15804, see Figure 5. Each of these stages will be explained in this section based on literature review.

4.3 Product stage

The earliest stage includes three sub-stages

- A1: Raw material supply
- A2: Transport
- A3: Manufacturing

These stages include all processes related to the provision of building materials. Whereas A1 solely consists of the operations with the raw materials, A2 encompasses transport between different locations like transport from suppliers to manufacturers and A3 is related to the manufacturing of the end product that will be delivered to the construction team (Stichting Nationale Milieudatabase, 2022). Therefore, an analysis solely based on stage A is called cradle to gate (Song et al., 2020). Part of this stage are also processes like waste, cleaning and packaging.

4.4 Construction process stage

- A4: Transport

This stage includes transporting building elements from the distributor to the construction site. In MPG calculations return transports are empty unless shown otherwise (Stichting Nationale Milieudatabase, 2022).

- A5: Construction – installation process

In this stage construction work itself is considered. This also includes waste on site, transport of waste and even equipment maintenance if this is more than 1% of the end calculation.

4.5 Use stage

- B1: Use

Chemical reactions involving material change and more mechanical processes (like erosion) are included in the use phase.

- B1-B5: Maintenance, repair, replacement and refurbishment

These stages include all actions to maintain the functional performance requirements of the building. Processes like maintenance, waste and production of new elements and transportation are considered here.

4.6 End-of-life stage

- C1: Deconstruction

This includes demolition works and or deconstruction.

- C2: Transport

Transport of building elements to processing locations like an incinerator, dump site or factory.

- C3-C4: Waste processing and disposal

The process involving the disposal, refurbishment or reuse of building elements.

4.7 Benefits and loads behind the system boundary

- D: Reuse-, Recovery- and Recycling- potential

This involves energy recovery or potential to recover or recycle products. This stage considers the benefits or burdens after disposal (Stichting Nationale Milieudatabase, 2022).

It is possible to design a framework that will clarify differences using these stages. The framework is shown in Table 10.

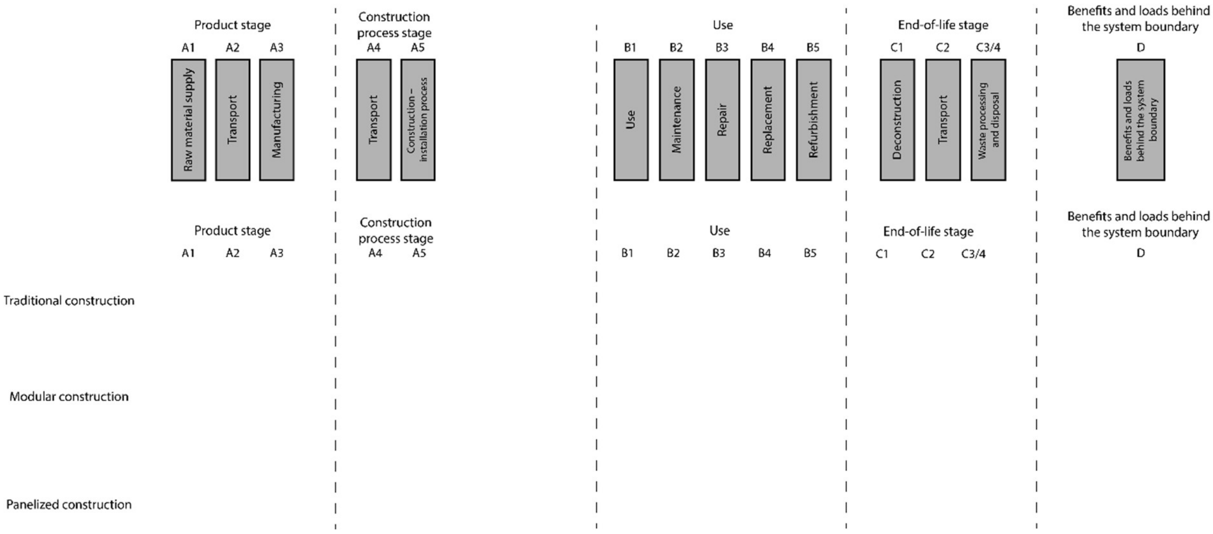


Table 10 Framework comparison LCA stages (own work)

4.8 Scope materials

As explained earlier in the introduction, the scope of this research is limited to the building elements leaving out installations and space plan. Interior walls and doors however are part of the assessment as these are different for each construction method. The scope is shown in Table 11.

These elements will be used as a framework in the rest of this chapter see Table 12. Installations and space plan are left out because these are not affected a lot by the chosen construction method.

Foundation	7%
Floors	16%
Structural elements	7%
Facades	18%
Roofs	6%
~~Installations~~	~~33%~~
~~Interior elements~~	~~13%~~ *
*Except for inner walls and doors	

Table 11 Scope research compared to all building elements in MPG of residential buildings (Stichting Nationale Milieudatabase, 2020)

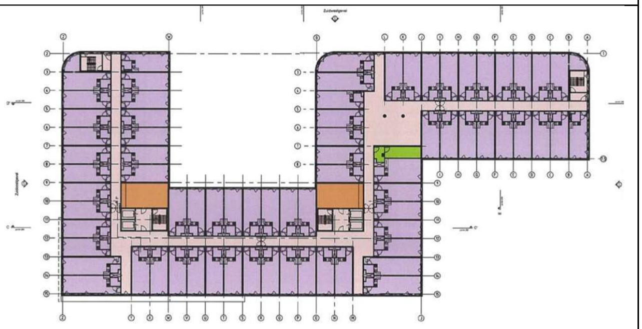
	Traditional	Panelized	Modular
Foundation			
Floors			
Structural elements			
Facades			
Roofs			

Table 12 Framework comparison construction materials

4.9 Construction phases onsite construction

In this section the construction process for traditional construction are investigated using the LCA phases as explained earlier. Firstly, the case will be introduced.

4.9.1 Introduction case onsite construction

	Change= Amsterdam Zuid-Oost Amsterdam 596 residential units 22 – 32 m^2 per unit 32.300 m^2 BVO 2017-2019
	

Change= Amsterdam Zuid-Oost will be used as a case for its use as a student complex with a repetitive layout with unit sizes around 20 m^2. Furthermore, this was one of the limited cases in which the researcher could obtain data.

Change= is a property manager renting out housing within a co-living concept. In their concepts, young professionals live in a high-density area on a relatively small floor area and share amenities like hospitality spaces, a gym and common areas. Currently, Change= operates three buildings one in Utrecht and the other two in Amsterdam (Change=, n.d.).

Change= Amsterdam Zuid-Oost was a construction project in Amsterdam from 2017 to 2019. The design was made by OeverZaaijer Architects. The total gross floor area measures 32.300 m^2 with 596 residential units and several shared amenities. The contractor for this project was BAM, the biggest contractor in the Netherlands.

4.9.2 Construction method

A method of onsite construction commonly used in repetitive designs such as studio apartments is cast in situ concrete tunnel form construction. This was also done for project Change=. Facades on the other hand were prefabricated floor edges and window frames. The bathrooms were also placed as prefab units.

Tunnel form construction is a common construction method that is often used for its economic advantages and considerable advantages in speed. Furthermore, this construction method is especially advantageous in highly repetitive buildings like studio apartments.

In tunnel form construction, a mold is created by combining two inverted L-shapes together and adding vertical elements on the outside. By pouring concrete in this mold an n-shaped monolithic piece is created consisting of two walls and a floor. By repeating this process with the same mold over and over buildings can be constructed relatively quickly (Gietbouwcentrum, 2007; The Constructor, 2014), see Figure 6

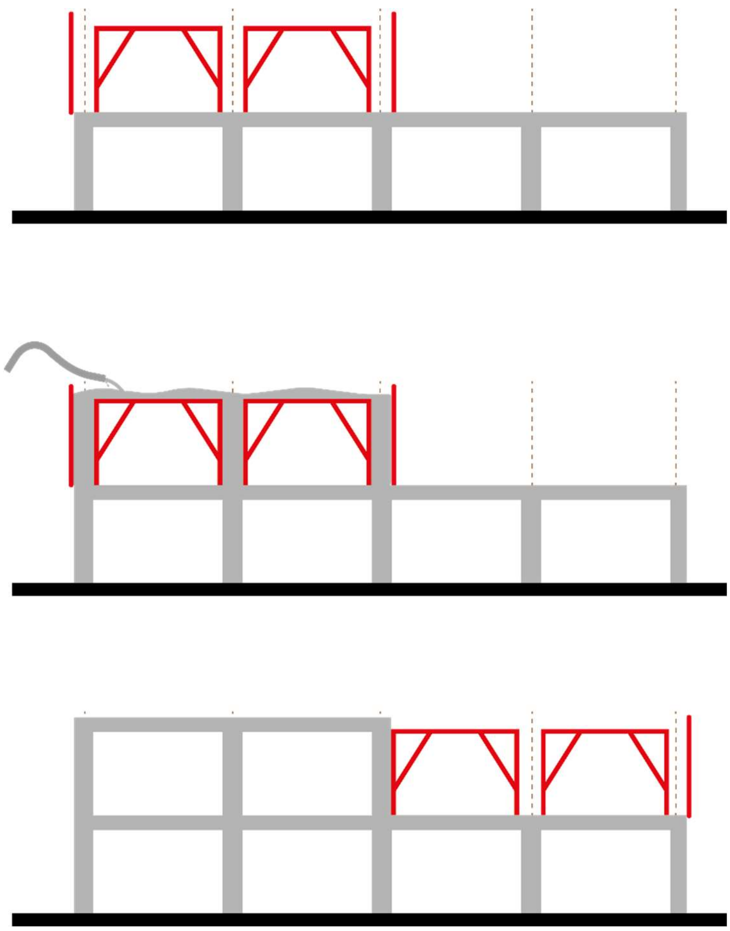


Figure 6 Tunnel form construction diagram (Own work)

4.9.3 Product stage

Suppliers take care of sourcing the materials.

4.9.4 Construction process stage

Transport of building materials goes from suppliers directly to site.

4.9.5 Use stage

It is unlikely that this building will need much maintenance especially since the elements that require a lot of care, finishings and installations are left out of this research.

4.9.6 End-of-life-stage

In the end-of-life stage, the building will be demolished. Because this construction method leads to directly coupled connections between floors and walls, disassembling this building will be tough (BCI GEBOUW, n.d.). However, it would be possible to crush the concrete parts of this building into granulates. Granulate is often used as a foundation layer in infrastructure projects (Fraanje et al., 2021).

4.9.7 Benefits and loads behind the system boundary

When concrete is reused as granulate the need for extra granulate production is lower. Therefore, the emissions saved by doing this can be considered a benefit beyond the system boundary (Fraanje et al., 2021).

Knowing that this is the most common construction method, it is no surprise that the LCA stages fit perfectly with this construction process, as seen in Table 13.

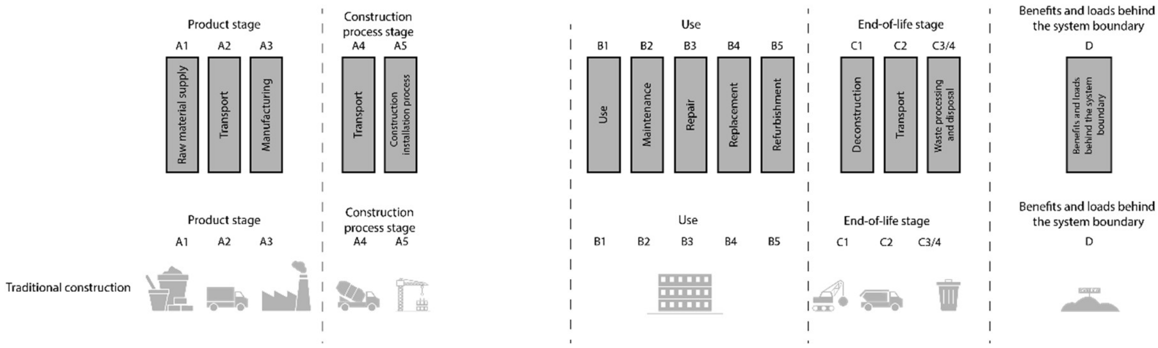


Table 13 Construction stages traditional case in framework

4.10 Materials traditional construction

This construction method uses a lot of cast-in-situ concrete. In this specific project, the facades were finished with prefabricated elements. The particular materials are shown in Table 14.

Traditional	
Foundation	Cast in situ concrete
Floors	Cast in situ concrete
Structural elements	Cast in situ concrete
Facades	Brick work outer layer and prefab timber frame inner wall
Roofs	Cast in situ concrete

Table 14 Traditional construction materials in framework

4.11 Construction phases modular construction

This section investigates the modular construction process.

As a case study Leerpark in Dordrecht was selected.

4.11.1 Introduction case modular construction

	Leerpark Dordrecht Dordrecht 333 studios 18-24 m^2 BVO 2022-2023
	

Leerpark Dordrecht is a Daiwa House Modular Europe project to build 333 residential units for students and young professionals in Dordrecht. The project is a collaboration between the municipality, Leerpark cooperation, and social housing cooperation Trivire (Groenendijk, 2022).

4.11.2 Construction method

Daiwa developed their process for constructing their concept in which modules are produced in their production facility in Montfoort. Here modules are manufactured by combining the concrete floors with a steel structural frame and filling the sides and top with timber frame elements. Bathrooms, fittings and finishings are all mounted in the factory. After production of the units, assembly of the building is done onsite limiting the works onsite. The onsite work is limited to facades, hallways, connecting the installations and roofs

Daiwa originates back to a company that only built temporary buildings. To this day most of their products can be returned to Daiwa as they have the facilities to refurbish their unit. Therefore their units have a specific residual value.

4.11.3 Product stage

Suppliers take care of the sourcing of materials. Also, transport and manufacturing of doors en windows are done by suppliers. Further, Daiwa has specific floors which are unique for their modules. Daiwa itself does the production of floor elements in its factory. Sourcing of concrete and other materials needed for production are outsourced.

4.11.4 Construction process stage

Transport of construction materials all goes to Daiwa’s production facility in Montfoort in the middle of the Netherlands. In this factory, their modules are assembled as described earlier. This whole process is very standardized and similar for each unit. These modules are transported to site on trailers and are assembled on site. The only elements that are made on site are the facades, hallways, connecting the installations and roofs

4.11.5 Use stage

The use phase is comparable to that of other buildings.

4.11.6 End-of-life-stage

In the end-of-life stage, Daiwa modular can dismantle buildings and return them to their factory. Here the units will be refurbished and reused. 80% of the materials in the units will be reused, made possible by their very standardized process and complete factory infrastructure, Figure 7.

Figure 7 Storage of used building elements Daiwa (own picture)

4.11.7 Benefits and loads behind the system boundary

As many of the materials will be reused in new or refurbished units there are significant benefits behind the system boundary. The life cycle of these materials is therefore not limited to one single life cycle but can by reused several times. In addition, Daiwa’s older modules are directly reused on other locations and from time to time, see Figure 8.

Figure 8 Refurbishment of used temporary office units at Daiwa (own picture)

Knowing what a construction process looks like for modular construction, it is possible to look into the LCA stages of this specific construction method. However, these phases do not correspond with the LCA stages as modular construction uses a slightly different approach. Several pieces of research have shown this difference (Alvanchi et al., 2012; Kamali & Hewage, 2016; O'Connor et al., 2016; Tavares et al., 2019). Kamali and Hewage (2011) also made Figure 9 to show the difference.

In the case of modular construction, stage A5 would include construction onsite and construction ofsite, transport to site and assembly onsite. This leads to an adapted figure combining LCA stages and the stages of modular construction, see Table 15.

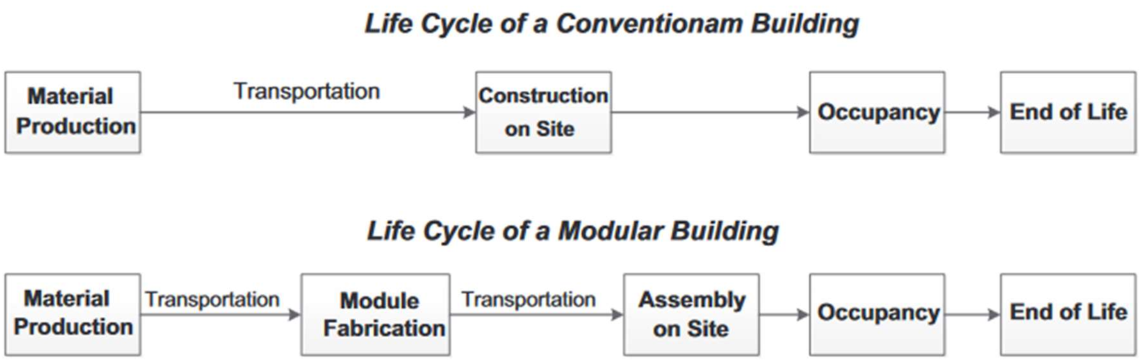


Figure 9: Difference between traditional and modular construction (Kamali & Hewage, 2016)

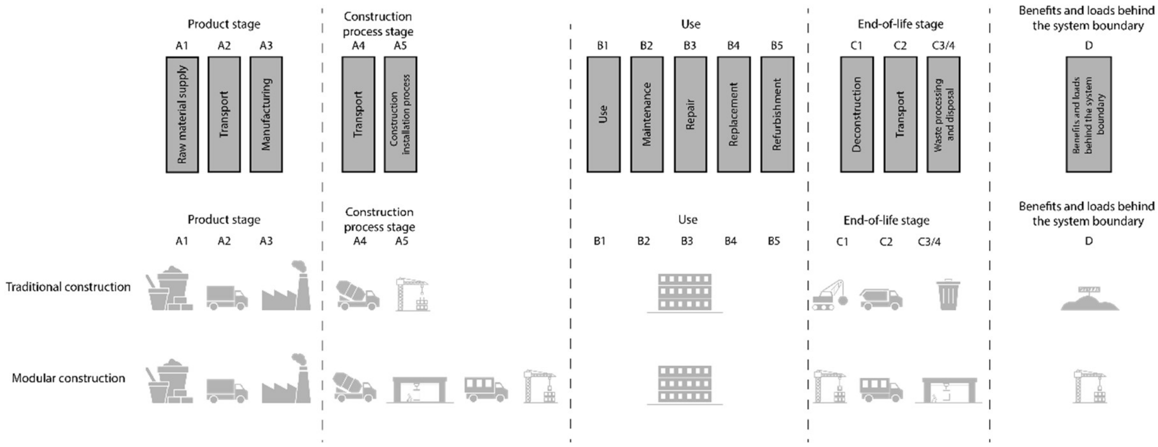


Table 15 Adapted LCA stages modular construction

4.12 Materials modular construction

In this case a mix of concrete, steel and wood is used. This project made use of the MIA/Vamil subsidy. This subsidy is introduced to stimulate circular initiatives. To apply for this subsidy the MPG can not be higher than 0,5 for a residential building and 50% of the materials has to be reused based on category 1 data from the NMD (Rijksdienst voor Ondernemend Nederland, 2022). This led to other material choices than in their regular projects that do not work with this subsidy. The particular materials are shown in Table 16.

Modular construction	
Foundation	Cast in situ concrete
Floors	Cast in situ concrete
Structural elements	Steel columns
Facades	Wood finishings combined with water-resistant foil
Roofs	TIMBER FRAME elements

Table 16 Modular construction materials

4.13 Construction phases panelized construction

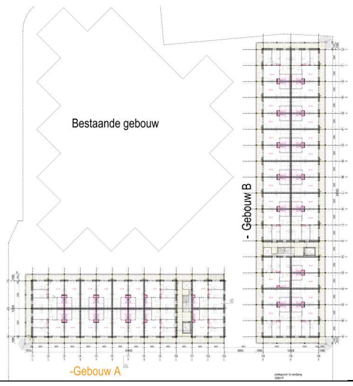
This section investigates the panelized construction process.

As a case study Houten hotel Almere was selected.

4.13.1 Introduction case panelized construction

Houten Hotel Almere is a project of a hotel near an already built restaurant. This wooden restaurant was realized in 2019. However, in 2021 the owners decided to expand it with a hotel next to it. Mirck Architecture designed two building blocks of 4 layers next to the existing restaurant resulting in an enclosed inner garden. Fletts was chosen as a contractor mainly as their construction method with wooden elements fits perfectly with the look of the restaurant. This was only the second assignment for this young start-up after an apartment complex in Culemborg.

This building has an outside gallery, unlike the other cases with an indoor corridor. The interior of this building will be unfinished wood.

	Houten hotel Almere 333 hotel rooms 20 m^2per room 3375,24 m^2 GFA 2022-2023
	

4.13.2 Construction method

Fletts works with independent contractors for the production of their prefab elements. In this specific project Willemsen Veenendaal was the supplier of the prefab elements and another team of professionals is assigned with assembly onsite. The panelized prefab elements are already equipped with windows, doors, sockets and outer finishes. Bathroom units are prefabricated by an extern supplier and installed onsite as a cube.

4.13.3 Product stage

Fletts focuses on wood construction which suppliers supply. This is done by suppliers.

4.13.4 Construction process stage

Building materials are transported to timber factories. As timber factories are often not prepared for assignments as big as the hotel, Fletts worked with 2 different factories.

The panels are transported to site with trailers and are assembled onsite by an individual assembly team.

4.13.5 Use stage

The use phase will be comparable to that of other buildings.

4.13.6 End-of-life-stage

It would be possible to disassemble the panels of this building. There is however not a specific use for these elements up front. On the other hand, engineering has already taken the ability to take the panels apart into account.

4.13.7 Benefits and loads behind the system boundary

There is no specific plan for the reuse of the building parts after the lifecycle of this building. However, this will be possible due to the detachable panel elements.

It is possible to fill in the framework by knowing what the different stages look like, see Table 17.

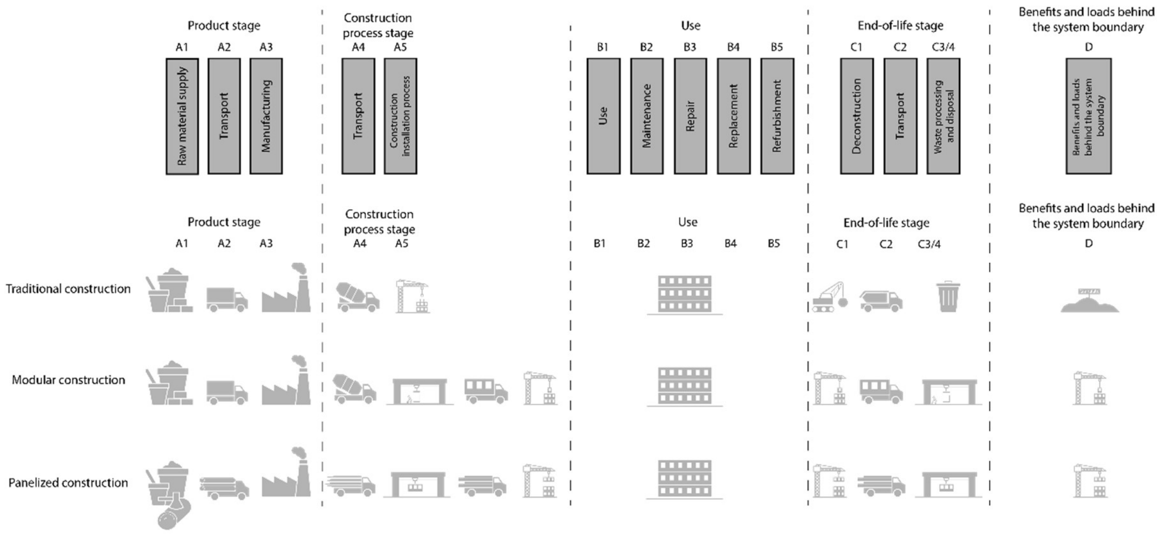


Table 17 Construction phases panelized construction

4.14 Materials panelized construction

This case was built with a mix of CLT and load-bearing timber frame walls. Further, this project also made use of the MIA/Vamil subsidy. The materials are shown in Table 18.

	Panelized
Foundation	Cast in situ concrete
Floors	CLT panels
Structural elements	CLT walls and wooden columns
Facades	Wood finishings on timber frame elements
Roofs	Timber frame elements

Table 18 Panelized construction materials

4.15 Conclusion

The aim of this chapter was to answer the following question:

What are the differences between offsite and onsite construction regarding construction processes and used materials?

Looking at the differences in the construction processes it is evident that the processes look different in the construction process stage and in the latter stage of the end-of-life stage and benefits and loads behind the system boundary stage, see Table 19.

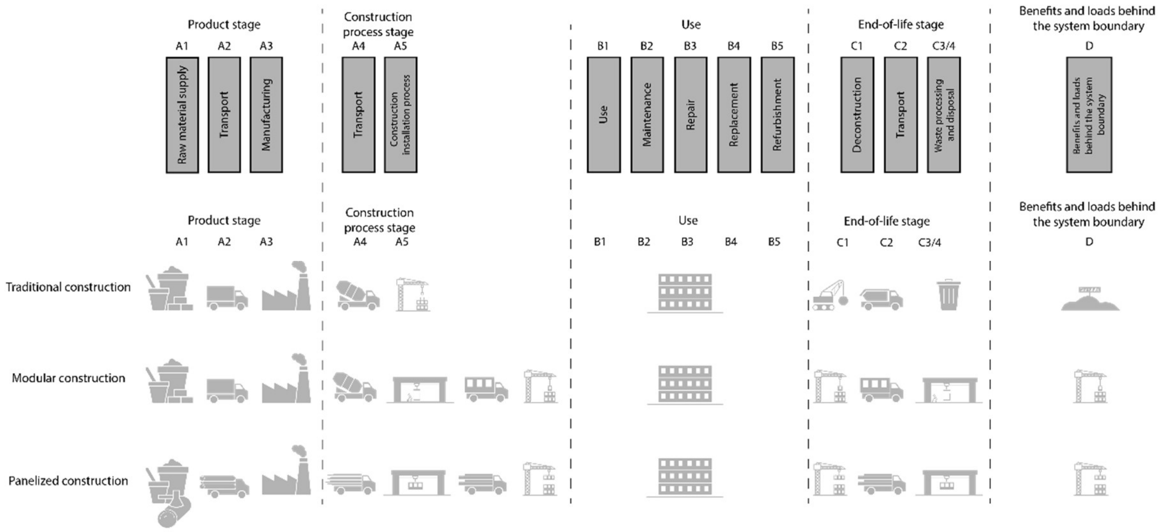


Table 19 Differences LCA stages construction methods

Looking at the materials of the construction methods it is clear that the cases all work with different materials. This is shown in Table 20.

	Traditional	**Modular**	**Panelized**
Foundation	Cast in situ concrete	Cast in situ concrete	Cast in situ concrete
Floors	Cast in situ concrete	Cast in situ concrete	CLT panels
Structural elements	Cast in situ concrete	Steel columns	CLT walls and wooden columns
Facades	Prefab concrete elements	Wood finishings on timber frame elements	Wood finishings on timber frame elements
Roofs	Cast in situ concrete	timber frame elements	timber frame elements

Table 20 Differences in materials construction methods

These differences will likely affect the environmental impact of the construction methods. The next chapter is going to assess the environmental impact of these cases. This will show whether the differences in this chapter affected the environmental impact.

5 Calculation environmental impact

5.1 Introduction

In this section, MPG calculations are made for three different cases. The differences between the cases will be presented first. Afterward, the process of making the MPG calculation will be explained. Then, the outcomes of the MPG calculations are presented. Finally, the chapter will end with a more in depth analysis of the MPG's going through each stage, answering the following question:

How does the MPG differ between offsite and onsite construction methods?

5.2 Comparability case studies

The 3 case studies have been realized by different contractors as explained earlier. The cases are shown in Table 21.

Traditional construction	**Modular construction**	**Panelized construction**
		
Change= Amsterdam Zuid-oost	Leerpark Dordrecht	Houten Hotel Almere
Bam	Daiwa Modular House Europe	Fletts
2017-2019	2022-2023	2022-2023
Student and starters housing	Student and starters housing	Hotel
596 units	333 units	498 units
22 - 32 m^2 per unit	18 or 27 m^2 per unit	20 m^2 per unit
32.300 m^2 GFA	9.062 m^2 GFA	7.500 m^2 GFA
10 levels	6 levels	4 levels

Table 21 Overview cases

NMD indicated the most important design parameters that influence the outcome of the MPG the most (Stichting Nationale Milieudatabase, 2020). Therefore, before comparing the MPG's of these buildings it is important to see how the cases differ on these parameters. This will make it easier to understand the differences in the MPG score later.

- The traditional case's gross floor area is much larger than the other cases. This would benefit this case in the MPG calculation.
- The number of stories is higher for the traditional case. This could benefit this case as the foundation will be shared with more floor area. On the other hand, this foundation would need to be heavier to carry this building, which would negatively impact the MPG of this building.
- The story height is very similar for the buildings.
- The traditional and modular cases have a better façade/floor ratio which will benefit the cases in the MPG calculations.
- The panelized case has a more closed façade which is beneficial in the calculation.
- The insulation values are very similar for the cases although the roofs of the offsite-produced buildings is slightly higher.
  The differences are shown in Table 22.

	Traditional construction	**Modular construction**	**Panelized construction**
	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
Gross floor area in MPG	24060	6981,6	3375,24
Number of stories	10	6	4
Story height	3	3,1	3
Façade/floor ratio	35%	41%	64%
Open/closed ratio	63%	63%	39%
Rc façade	4,5	4,5	4,5
Rc roof	6	6,3	6,3

Table 22 Relevant differences in the MPG parameters between the cases

5.3 MPG calculation

The calculations are based on the MPG's submitted for the buildings' environmental permit to ensure reliability. The calculations were made by different professionals specialized in MPG calculations. Also the MPG's were not made using the same MPG tool, and the traditional case calculation was made based on older guidelines. Also the scope of these MPG's was different then the scope of this research. Therefore these calculations were reentered into the latest version of the MPG GPR tool. Both offsite cases exist out of two smaller building blocks with a separate MPG calculation each. The most representative building block was selected and reentered. A file in the appendix shows the differences between the orinal MPG's and the MPG's used in this comparison. There are more MPG tools available but the GPR tool was easily accessible for the researcher. The scope of this MPG calculation does not include:

- Finishings
- Services
- Spaceplan (Except for inner walls and doors)

5.4 MPG results

The results of the MPG calculation are shown underneath in Table 23.

	Change= Amsterdam	**Leerpark Dordrecht**	**Houten Hotel Almere**
	Traditional construction	Modular construction	Panelized construction
Relevant differences for MPG			
Floor area	24080 m^2 BVO	6981,6 m^2 BVO	3375,24 m^2 BVO
Stories	10	6	4
Façade/floor ratio	35%	41%	64%
Open/closed facade ratio	63%	63%	39%
MPG outcomes			
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

Table 23 Comparison of MPG results

5.5 Building elements and materials

It is interesting to look at the MPG scores of the separate building elements as shown in Table 24. As the buildings differ in composition, the influence of different building elements on the outcome of the MPG differs. One building does have a larger roof area than the other buildings for example.

	Traditional	Modular	Panelized
Foundation	0,057	0,036	0,037
Floors	0,124	0,04	0,095
Structural elements	0,096	0,052	0,01
Facades	0,057	0,1	0,111
Roofs	0,015	0,003	0,024
Inner walls	0,033	0,021	0,03
Stairs	0,003	0,002	0,006
Total	**0,385**	**0,254**	**0,313**

Table 24 Impact of separate elements

Looking at the impact of the different elements the high value of the floors and inner walls for traditional construction stand out, see Table 24. This can be traced back to the high usage of concrete in these elements. The modular building is the only one dealing with the impact of load-bearing elements. This stems from the fact that the other building methods use residential separating walls that are both load-bearing and separating. At the same time, steel profiles must be entered separately in the MPG tool as load-bearing elements. The panelized building has a significantly higher impact on the façade because this design has specifically large façade areas compared to the floor area. Secondly, the specific façade finishing of this design has a high environmental impact. This can be seen in Table 25. In the next section the outcomes of the MPG outcome will be explained further for each stage.

	Traditional construction	**Modular construction**	**Panelized construction**
	Brickwork	Pine wood	Moso Bamboo Extreme
A1-3	0,01	0,006	0,025
A4-5	0,006	0	0
B	0,001	0,006	0,021
C	0,003	-0,002	0
D	-0,002	0	-0,007
	0,018	0,01	0,039

Table 25 MPG scores of different facade finishings on the panelized case study

5.6 Product stage

MPG Building	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

The comparison shows that panelized construction has the lowest environmental impact while traditional construction has the highest impact in the initial stages. Phases A1-A3 only measure the impact of construction materials. This assessment shows that predominantly wooden construction has a lower impact than the mostly concrete building. This seems to be in line with literature in which wood is considered a sustainable construction choice (van der Veen & Hemelaar, 2022). This is also shown when assessing the MPG score of the interior walls separately like in table 26. In the table the interior walls in the case of Houten Hotel are entered as concrete walls like in the traditional case as well as in timber frame walls like in the panelized and modular case. The comparison shows that the impact of timber frame walls is significantly lower with almost factor 10. However, this is a comparison between load bearing walls and solely separating walls.

Table 26 MPG impact stages A1-A3 for both a poured concrete wall (traditional) and prefab timber frame walls (panelized) in the panelized case

MPG product	Poured concrete wall	Prefab timber frame walls	Prefab timber frame walls
	Traditional	Panelized	Panelized
A1-3	0,122	0,013	0,013
A4 -5	0,026	0	0
B	0	0	0
C	0,008	0	0
D	-0,016	-0,004	-0,004
	0,14	0,009	0,009

This comparison fits well with the findings in chapter 4, which showed that the activities are very similar in this stage but the materials differ. The difference in MPG score can here be traced back to the use of different materials.

5.7 Construction process stage total MPG

MPG Building	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

The impact in the construction process stage depends on the materials used in the building when using the available MPG tools. Therefore, different transport logistics for the processes used in these buildings are not assessed differently. Conversely, when a supplier decides to make an EPD of its product stage A4 is assessed by using the default value of 150 kilometers. Stage A5 is assessed by the tools used to mount the building elements. The EPD for a steel profile, for example, considers a crane's fuel consumption. The supplier calculated how long it takes to install 1 kg of construction steel and how much fuel a crane would need. Using a crane in an industrialized process will be more efficient than in a unique on-off project, but this is not recognizable in the MPG calculation.

The MPG comparison shows that the traditional project has a higher impact while the offsite construction methods have a similar much lower impact where panelized construction is slightly better. This is because concrete needs a lot of energy for transport and construction and the onsite case uses a lot of concrete. This difference is also shown in table 27. On the contrary, modular construction works with limited concrete and a lot of lighter elements, resulting in lower transport emissions. However, panelized construction works with even less concrete and wood is associated with even lower transport emissions.

Table 27 MPG impact stages A4-A5 for both a poured concrete wall (traditional) and prefab timber frame walls (panelized and modular) in the panelized case

MPG product	Poured concrete wall	Prefab timber frame walls	Prefab timber frame walls
	Traditional	Modular	Panelized
A1-3	0,122	0,013	0,013
A4 -5	0,026	0	0
B	0	0	0
C	0,008	0	0
D	-0,016	-0,004	-0,004
	0,14	0,009	0,009

This comparison does not fit with the findings in chapter 4, which showed that the activities are very different at this stage. There is no option in the MPG tool to fill in that the transport for the different construction methods is different. This is especially relevant for the concrete floor which is used in the traditional as well as in the modular case. The concrete for the modular contractor is delivered from a concrete factory nearby whereas the concrete from the traditional case was delivered from a supplier farther away which is important as concrete transport uses significant energy (Pulselli et al., 2008). Also the amount of spillage of offsite production is considered to be lower than that of onsite construction but this differentiation cannot be entered into the MPG tool.

5.8 Use stage

MPG Building	**Change= Amsterdam**	**Leerpark Dordrecht**	**Houten Hotel Almere**
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

When assessing the use stage of building materials: impact of maintenance, possible replacements and emissions within the building life are measured.

Concrete used in the traditional project is associated with very little maintenance during the use stage. The panelized project was designed with a lot of wood with is associated with more maintenance and replacements. The wooden windows like the ones used in this project have to be painted every 12 year while the aluminum windows in the modular project do not need specific maintenance (Gideon, 2022a), see table 28.

Table 28 MPG for both aluminum window frames (traditional and modular) and wooden window frames (panelized) in the panelized case

MPG product	**Aluminum window frames**	**Aluminum window frames**	**Wooden window frames**
	Traditional	Modular	Panelized
A1-3	0,014	0,014	0,008
A4-5	0	0	0
B	0	0	0,001
C	-0,001	-0,001	0
D	-0,004	-0,004	-0,002
	0,009	0,009	0,008

Also, the roofs of the panelized case have a significant impact on the MPG in the use phase. That makes sense as this building has less floors than the other cases resulting in more roof area per GFA. This gives the panelized case more square area of roof finishings compared to the other cases negatively impacting the MPG score, see Table 29.

Table 29 MPG for the roofs in the different cases

MPG product	EPDM glued	Double layered bitumen	EPDM mechanically fixed
	Traditional	Modular	Panelized
A1-3	0,002	0	0,004
A4-5	0	0	0
B	0,001	0	0,003
C	0	0,001	0,001
D	0	0,001	0
	0,003	0,002	0,008

This comparison fits with the findings in chapter 4, which showed that the activities are similar in this stage but the materials are different. The different materials did lead to different MPG outcomes for this part.

5.9 End of life stage

MPG Building	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	0,385	0,254	0,313

The end of life stage includes the impact of dismantling, transport and waste processing. Concrete is hard to process and cannot easily be reused and therefore the traditional case has the highest score, see table 30. On the other hand, wood as used in the panelized project is relatively easy to dismantle and can be processed as bio fuel for powerplants which directly delivers energy according to the NMD database. Therefore this stage is negative in this case. Modular construction is somewhere in between partly because there was a separate option to classify steel as design for reuse which allows for a lower impact score for dismantling this element.

Table 30 MPG for concrete floors (traditional) and CLT floors (panelized) in the panelized case

MPG product	Traditional construction	Traditional construction	Panelized construction
	Cast concrete floor 250 mm	Cast concrete floor 50 mm + steel	Cross Laminated Timber floor 200 mm
A1-3	0,037	0,076	0,086
A4-5	0,002	0,005	0,003
B	0	0	0
C	0,014	0,010	-0,036
D	-0,004	--0,046	0
	0,049	0,044	0,053

This comparison does not fit with the findings in chapter 4. Both offsite contractors developed their buildings in a way which would enable reuse at the end of lifetime of the building. Unfortunately the MPG tool is coupled to the NMD tool which only allows for the selection of timber wall systems that are burned for energy production and not used again. This is negatively impacting the MPG score of the panelized and modular system.

5.10 Benefits and loads behind the system boundary

MPG Building	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

Benefits and loads behind the system boundary define the impact after waste processing. For example, the brickwork used in the traditional case can be crushed and used as masonry granulate. The energy saved by not producing masonry granulate can be deducted from the total environmental impact. As steel is designed for reuse in the modular project, a lot of energy will be saved by reusing this project's steel structure; therefore, this project has the best score here, see table 31. For the panelized project the reuse of elements like the fittings of window frames is also recognized.

Table 31 MPG of structural elements in three cases

MPG product	Traditional	Modular	Panelized
	Concrete structure	Steel structure	Wooden structure
A1-3	0,083	0,109	0,016
A4-5	0	0,007	0,001
B	0,000	0	0
C	0,006	0,01	0
D	-0,011	-0,074	-0,006
	0,096	0,052	0,011

However, this calculation does not take into account how the different construction methods operate. Modular construction, for example, is designed to be dismantled in units at the end of its lifetime to use it again in another location or refurbish it in one of their halls dedicated to refurbishing elements. This does not fit with the findings in chapter 4. On the other hand, it was possible for steel elements it was possible to fill in that the elements were designed for reuse. For these elements it was possible to take into account that these elements can be reused. This was not possible for the wooden structural elements.

5.11 Conclusion

MPG Building	Change= Amsterdam	Leerpark Dordrecht	Houten Hotel Almere
	Traditional construction	Modular construction	Panelized construction
A1- A3	0,307	0,306	0,303
A4 – A5	0,036	0,017	0,015
B	0,024	0,044	0,066
C	0,046	0,014	-0,030
D	-0,028	-0,128	-0,041
Total	**0,385**	**0,254**	**0,313**

This chapter answered the following question:

How does the MPG differ between offsite and onsite construction methods?

The total MPG value is the lowest for the modular project, highest for the traditional project and somewhere in between for+ the panelized project. This is however highly dependent on the relevant differences between the project as shown in Table 22. However, the environmental impact of these cases is lower for offsite construction. Modular offsite construction got a lower environmental impact than offsite panelized construction.

Remarkably, the traditional project would have a lot of parameters in its favor but it still has the highest environmental impact as measured in the MPG. Unfortunately, the MPG calculation only uses available data from the materials and does not enable to specify the construction method.

Therefore, the differences in construction processes identified in chapter 4 are not recognized in the MPG for calculating the environmental impact.

This comparison is more of a comparison of the environmental impact of a concrete building (traditional), a steel concrete hybrid (modular) and wooden building (panelized), the findings concerning materials from chapter 4.

After comparing the environmental impacts of the cases, the next chapter will continue by looking into possibilities to lower the environmental impact of a building.

6 Towards a lower MPG

6.1 Introduction

In this section suggestions are presented for contractors of offsite construction methods to lower their MPG answering the question:

How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products?

In the first section ideas and suggestions are found by doing a literature review and own findings in the earlier parts of this research

Looking at the findings from this research and a comparative MPG research in residential buildings by W/E adviseurs (2022) and in non-residential buildings by DGBC (2022) 4 methods were identified to achieve a lower MPG.

- Limiting the use of materials
- Choosing different materials
- Use more cat 1 or 2 data
- Enter a longer lifespan for a building

These methods will be discussed in this chapter.

6.2 Limiting the use of materials

The first and most obvious choice to limit the MPG score and environmental impact would be to limit the use of materials. As the MPG measures the quantity of materials using less material will always lead to less environmental impact.

The DGBC (2022) comparison showed that this strategy is unintentionally used in cases when a lighter foundation can be used depending on location and subsurface. This lowers the MPG significantly without further impact for the building.

6.3 Choosing different materials

Secondly, opting for other materials could lead to a lower MPG value and lower environmental impact. This was also mentioned by W/E adviseurs (2022) as the most important method to limit MPG. The inner walls for example prove to be a lot worse for the environmental impact when they are made out of concrete instead of wood see Table 26. Biobased materials like wood prove to be more sustainable in the example.

A strategy that can also be chosen is working with reused materials instead of new virgin materials (van der Veen & Hemelaar, 2022). This strategy was not used in one of the cases. It is possible in the MPG tool to classify materials as reused, see Figure 10. When this option is selected, only 20% of the new product's environmental impact will be calculated (Stichting Nationale Milieudatabase, 2022). Using partly recycled materials is also an option when using concrete for foundations (Dutch Green Building Council, 2022).

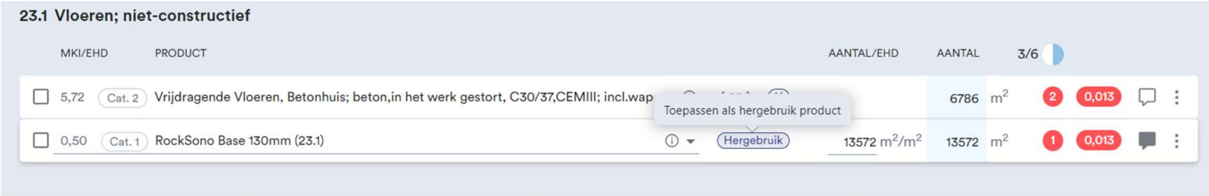


Figure 10 Screenshot of GPR MPG tool showing the reuse button

Biobased materials like wood or mycelium could also help to bring down the environmental impact. Even though wood construction did not score the lowest MPG in this comparison, MPG comparisons undertaken by W/E Adviseurs (2022) and DGBC (2022) have shown that wood construction does help in lowering the MPG. Also, research by TNO (2022) has shown that wooden construction methods would outperform traditional construction by far if the MPG method were to be slightly adapted to take sequestrated carbon into account.

6.4 Use more cat 1 or 2 data

When comparing the MPG's, it is noticeable that one case has a lot more type 1 data than the other. A markup factor applies to the category 3 data, because experience has shown that untested data often understated environmental impact. Because the inventory data are less specific, and to encourage category 1 and 2 data to be offered to the database, there is a markup factor of 30% for cat 3 data. This makes the difference in the composition of data types very relevant (Stichting Nationale Milieudatabase, 2022).

Looking at the CLT panels used in the calculation for the panelized buildings indicate the relevance of type 1 data directly, see Figure 11. The category 3 data in this case leads to a MPG value that is more than 14 times higher than the type 1 data.

Figure 11 Screenshot GPR MPG tool with type 1 and type 3 data for CLT floor panels

Unfortunately, there is not enough category 1 data in the NMD yet (Gideon, 2022a; van der Veen & Hemelaar, 2022). This can also be seen in Figure 12 where the composition of data types within the NMD is shown. Therefore, to encourage more category 1 data in the database subsidies were started. Also, to make sure more innovative products are added to the database the NMD has started a program to encourage startups to submit their EPD's and LCA's to the NMD for free (Nationale Milieudatabase, 2022). This was much needed as the costs for entering a product into the NMD are high, especially for these young startups that usually have a smaller product portfolio (I. Bak, personal communication, November 21, 2022; Gideon, 2022a; Oostdijk et al., n.d.; van der Veen & Hemelaar, 2022).

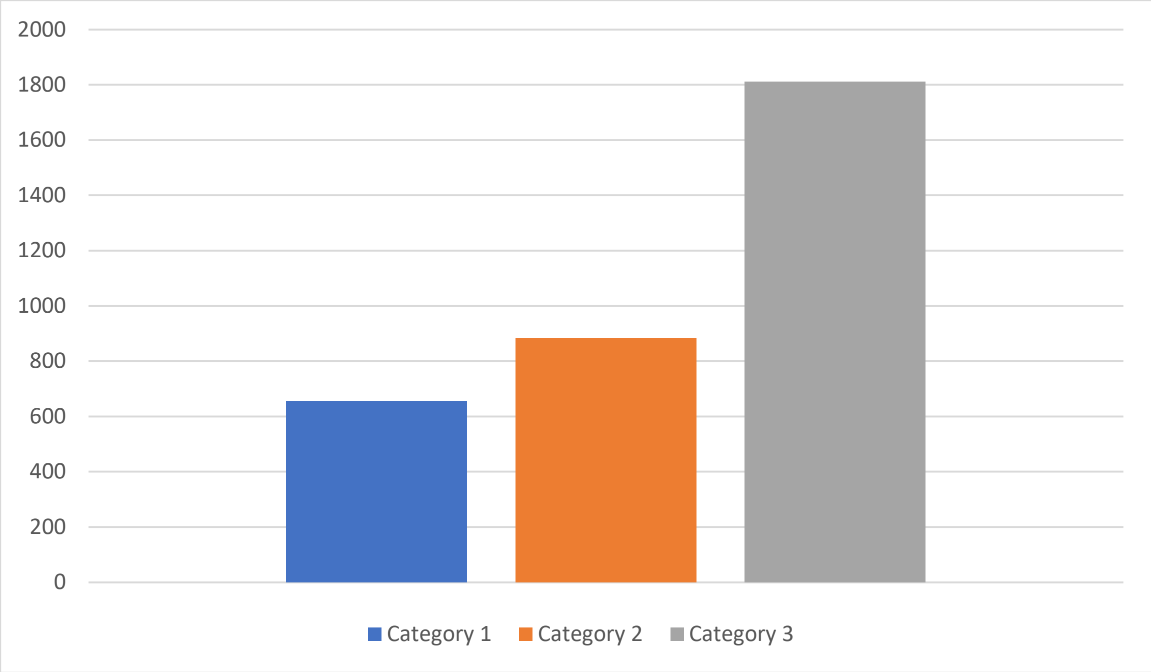


Figure 12 Composition of data types in NMD on 11th of January 2022 (Gideon, 2022a)

To steer towards a lower MPG value working towards more type 1 data would be compelling. It is possible to choose materials entered into the NMD or convince the existing supplier to enter data into the NMD.

6.5 Enter a longer lifespan for a building

The MPG calculation is a comprehensive formula shown underneath:

$$\frac{Sum\ of\ shadowcost}{Gross\ Floor\ Area\ /\ Life\ span\ building} = MPG$$

The default life span of a building in the MPG is 75 years for residential buildings. However, it is possible to enter a longer life span to lower the total MPG score in line with a publication of W/E advisors (W/E adviseurs, 2020). This publication allows for an extra-long lifespan when there are beneficial factors for robustness and adaptability. Therefore, by scoring a building on the varying aspects as shown underneath it is possible to obtain a bonus based on its characteristics, see Table 32.

Calculation tool MPG life span					
Max bonus	100%				
Use	Residential				
Characteristic	Option	Score	%	Factor	Bonus
Building quality			50%		26,3%
Robustness			60%		21,0%
Robustness design	Excellent	3	70%	21%	21,0%
Futureproof construction	Standard	0	30%	9%	0,0%
Identitiy			40%		5,3%
Aesthetic	High	1	80%	16%	5,3%
Landmark	Standard	0	20%	4%	0,0%
Adaptability			50%		19,3%
Building volume			20%		2,7%
Expandability	High	1	80%	8%	2,7%
Decreaseability	Standard	0	10%	1%	0,0%
Replaceability	Standard	0	10%	1%	0,0%
Layout within volume			40%		12,0%
Divisibility	Standard	0	40%	8%	0,0%
Adaptability within unit	Excellent	3	60%	12%	12,0%
Services			40%		4,7%
Adaptability technical quality	High	1	70%	14%	4,7%
Expandability services	Standard	0	30%	6%	0,0%
Total characteristics					45,6%

Conclusion		
Use	Residential	
Default	75	years
Bonus	46,0%	
Final life span	**110**	years

Table 32 Sample spreadsheet for determining specific building life span based on (W/E adviseurs, 2020)

This strategy was not used in one of the case studies from this research but in the comparison of W/E adviseurs one case used this strategy. Considering the buildings' characteristics, the offsite cases would be eligible for this bonus. However, this loophole is not very well known and not often used (Anonymous interviewee, personal communication, October 26, 2022).

6.6 Conclusion

This chapter answered the following question:

How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products??

Looking at the earlier comparison and literature four different methods to lower the MPG of a building were identified. Two of these strategies would also help to bring down the environmental impact.

To bring down the environmental impact:

1. Limiting the use of materials
2. Choosing different materials

To bring down the MPG score:

3. Use more cat 1 or 2 data
4. Enter a longer lifespan for a building

This theoretical approach has led to the four strategies. The next chapter will test their viability and effectiveness.

7 Daiwa towards a 25% lower MPG

In this part the suggestions of chapter 6 will be translated into specific actions that Daiwa can take to lower their environmental impact with 25%. In this case, recommendations will be made to lower the MPG score of the case Leerpark. This case was built with Daiwa's own modular construction method. First suggestions were drawn up based on the previous chapter. Then, these suggestions were tested on their feasibility for this specific organization through semi-structured interviews with an engineer. Also, the improvements were tested on their effectiveness in the MPG calculation. These recommendations would be applicable for different contractors using different types of offsite and onsite construction methods.

What are the possibilities for Daiwa Modular House Europe to reduce the environmental impact of their project Leerpark Dordrecht by 25%?

7.1 Limiting the use of materials

It is unlikely that Daiwa can use less materials in their current system. The system is already optimized for the minimal use of material through the uniform process in which it is relatively easy to cut down on quantities as compared to onsite construction. This uniform constant process has been practiced for years and optimized. This also resulted in minimal use of materials to avoid additional costs.

For example, looking at the concrete floors shows that these floors already have a minimal amount of concrete with a very thin layer of concrete (50 mm) through the combination with steel profiles. This floor was a result of the ongoing iterations to the floor initially used in the temporary units (container units). The first models of these containers were even equipped with wooden floors which proved not to feel very high quality. However, as the units still had to be lightweight despite the switch to concrete a very light concrete structure was engineered.

Also, an engineer of Daiwa confirmed that using fewer materials is probably impossible. In fact, the current modules are relatively light and making even lighter modules will affect the design of the foundation and more concrete will be needed in the foundation. This comes from the fact that lighter modules will be blown away when these are too light. These wind forces result in pulling forces in the foundation making a heavier foundation necessary, see Figure 13. This requires all new engineering of the foundation and will probably lead to additional concrete in the foundation.

However, it is unlikely that other contractors using a specific construction method are dealing with this problem. Daiwa is extra concerned with the weight of their modules as they are restricted by their trucks' maximum load-bearing capacity. Daiwa already did focus on leaving out materials to save weight. This is possibly not done by other contractors yet leaving room for improvement.

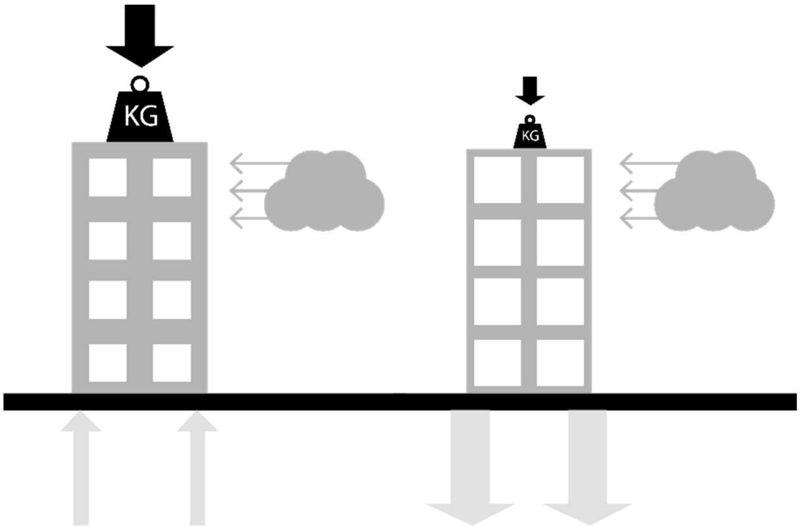


Figure 13 Illustration showing the effect of a lighter building on the foundation (own work)

7.2 Choosing different materials

To find iterations to the case of Leerpark the MPG was used. Figure 14 and Table 33 show the specific MPG impacts per element. To find different materials with a lower environmental impact, each building element with an impact of 5% or more in the total MPG was evaluated.

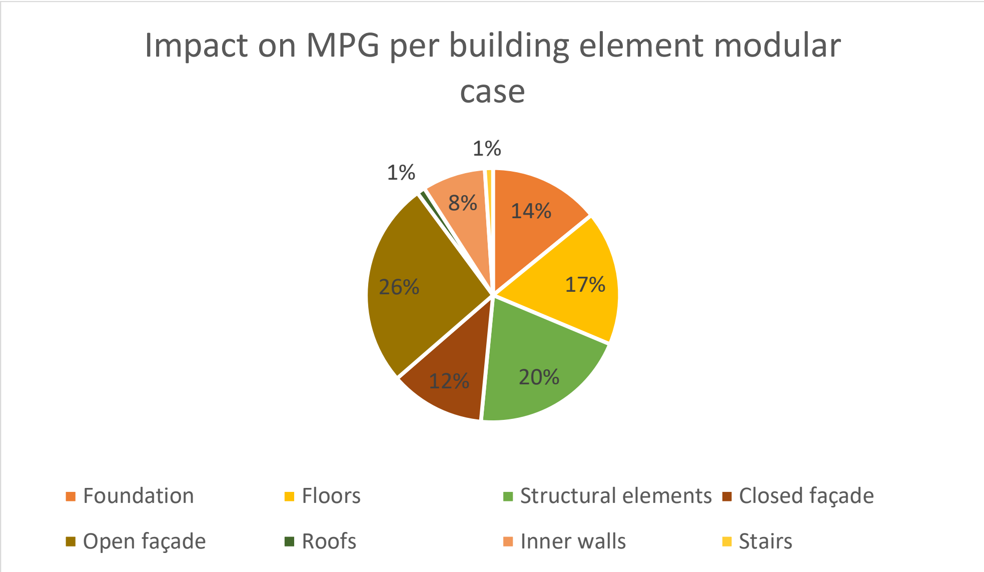


Figure 14 Impact on MPG per building element modular case

Specific MPG impacts modular case		
Foundation	0,036	14%
Floors	0,043	17%
Structural elements	0,052	20%
Facade closed	0,031	12%
Facade open	0,067	26%
Roofs	0,003	1%
Inner walls	0,021	8%
Stairs	0,002	1%

Table 33 Specific MPG impacts modular case and percentages

7.2.1 Foundation

Unfortunately, not many options are available to improve the environmental impact of the foundation. Some options are available in the market, like hollow prefab foundation piles, but unfortunately, these options are not available in the NMD (Smienk, 2016).

7.2.2 Floors

There would be some improvements possible when looking at the floors currently used. The existing floors consist of steel profiles, EPS insulation and concrete. Although this case uses minimal concrete, wooden floors would probably lead to a lower environmental impact (Lopez & Froese, 2016).

Dias et al. (2021) showed that soft wood-based floors have the lowest environmental impact compared to other wooden floors. On the other hand, the CLT floors already proved to lead to a further reduction in MPG with similar spans when comparing the panelized cased to the modular case.

In dialogue with an engineer, two alternatives were entered into the MPG tool. The specifics of the parameters are shown in table 34. The CLT alternative is based on the design of the Houten Hotel Almere from the earlier comparison. In contrast, the timber frame alternative is based on the design of HOUTbaar, a competitor of Daiwa.

Original			
	Units	Data category	MPG value
Reinforced concrete C20/25	50 mm	Cat 2	0,012
Steel	N/a	Cat 2	0,031
Rock sono base 130 mm	N/a	Cat 1	0,007
			0,05

Table 34 Floor composition as in MPG, current state

Alternative CLT			
Derix X-lam CLT panels	N/a	Cat 1	0,012
Floor elements gypsum panels and insulation	20 mm	Cat 2	0,012
			0,024

Table 35 Floor composition as in MPG, CLT alternative

Alternative timber frame			
timber frame element	N/a	Cat 2	0,01
Floor elements gypsum panels and insulation	20 mm	Cat 2	0,012
Insulation Knauf	3,5 m^2K/W	Cat 1	0,006
			0,028

Table 36 Floor composition as in MPG, TIMBER FRAME alternative

In conclusion, the alternative with a CLT floor would lead to the most considerable reduction of 52%, see Figure 15 MPG scores of different variants for floors. The total MPG as shown in part 5.11 is decreased with 10%. Figure 14 shows that the MPG value of the original floors would be 0,04. However, this is not entirely correct as structural reinforcements in the floor would be left out of the design when another floor is chosen; therefore in this comparison, the MPG value of the original value is 0,05.

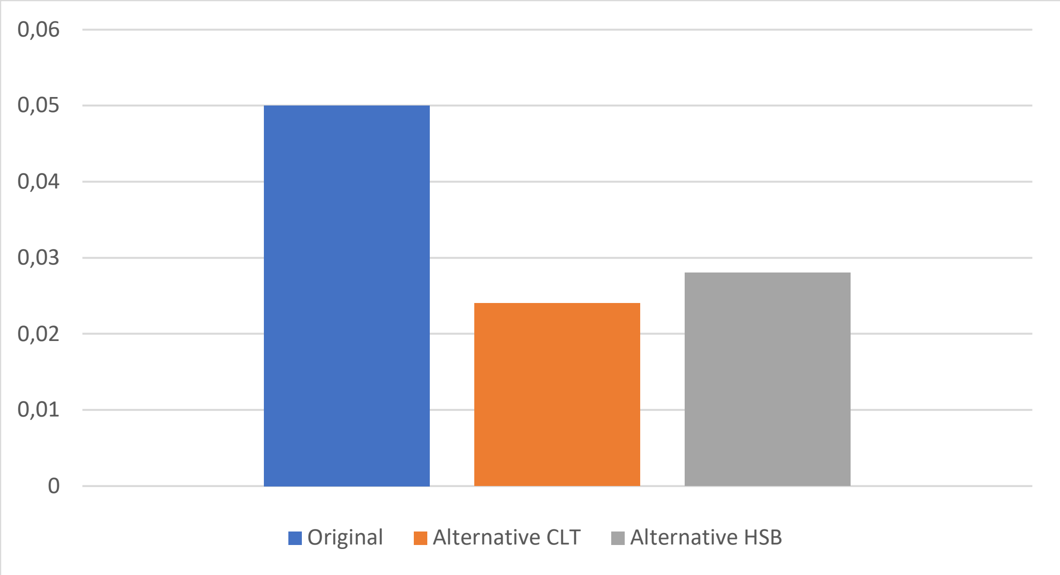


Figure 15 MPG scores of different variants for floors

7.2.3 Structural elements and inner walls

In the current situation the structural elements consist of steel profiles. Table 37 shows that the wood structure will likely lead to a lower MPG. This switch to biobased materials has already been indicated as a prominent option to reduce MPG.

MPG product	**Traditional case**	**Modular case**	**Panelized case**
	Concrete structure	Steel structure	Wooden structure
	0,096	0,052	0,011

Table 37 Comparison of the different MPG impacts of different structural elements

This seems feasible for modular studios as two Dutch competitors have already incorporated this in their modular construction method, namely Finch buildings and HOUTbaar. Looking at Figure 16 and Figure 17, it is noticeable that both concepts work with different load-bearing structures. GeWOONhout works with load-bearing beams and columns, while Finch works with load-bearing CLT walls.

Figure 16 Construction site geWOONhout concept (geWOONhout, n.d.)

Figure 17 Structure module Finch buildings (Finch Buildings, n.d.)

Firstly looking at CLT elements, Figure 18 shows that the units' walls, floors and ceilings are made with CLT elements. However, this chapter focuses on the vertical structural elements as the floors are already discussed. Therefore in this suggestion, the separating walls will be replaced with CLT as these load-bearing walls carry a double function as structural element and unit separating element.

Figure 18 Assembly of Finch CLT modules (Finch buildings, 2020)

Two alternatives are drawn up for Leerpark Dordrecht. The first CLT alternative is based on the modules of Finch. The second alternative with a mix of CLT with timber frame and extra columns is derived from the design of Houten Hotel Almere.

Original			
Element name	Parameters	Data category	MPG value
TIMBER FRAME wall element inc insulation	N/a	Cat 2	0,012
Steel designed for reuse	N/a	Cat 2	0,02
			0,032

Table 38 Seperating walls composition as in MPG, current state

Alternative CLT			
Derix X-lam CLT panels	N/a	Cat 1	0,016
			0,016

Table 39 Seperating walls composition as in MPG, CLT alternative

Alternative timber frame and CLT			
Timber frame element	N/a	Cat 2	0,01
Derix X-lam CLT panels	N/a	Cat 1	0,008
Wood columns European softwood	250 mm; 200 mm	Cat 2	0
			0,018

Table 40 Seperating walls composition as in MPG, timber frame and CLT alternative

In conclusion, the alternative with CLT would lead to the most considerable reduction of 50%, see Figure 19. The total MPG as shown in part 5.11 is decreased with 6%. The MPG impact of structural elements here is lower than in Table 37 as many structural elements are incorporated into the floors. Also, the MPG impact of interior walls here differs from Table 33. This is because interior doors are included in Table 33 but not here.

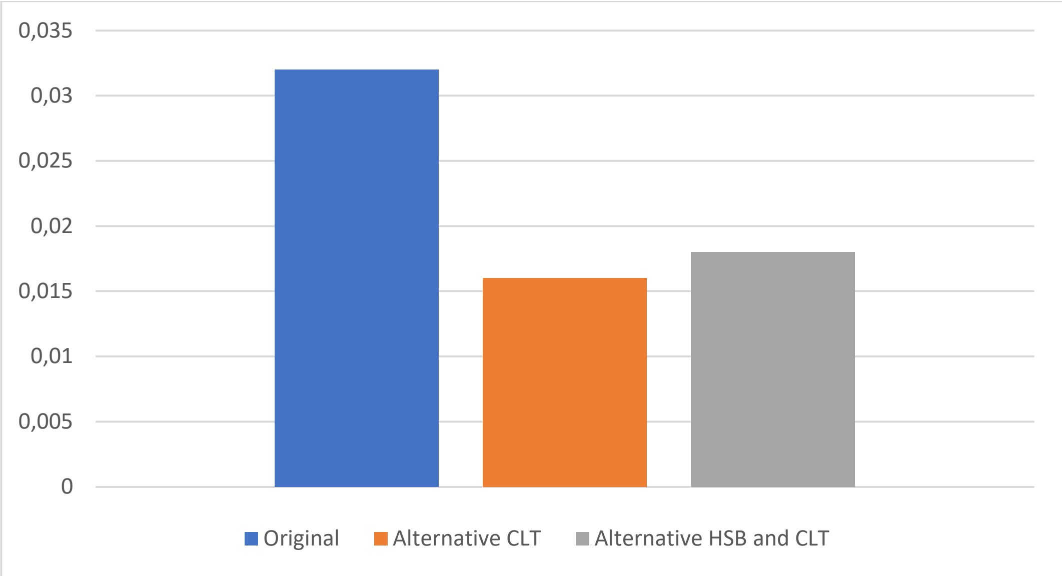


Figure 19 MPG scores of different variants for separating walls

7.2.4 Open façade

Looking at the open façade, it would be possible to switch to wooden frames instead of aluminum ones. This would lead to a reduction of 15% as shown underneath. The total MPG as shown in part 5.11 is decreased with 8%.

Original			
Element name	Parameters	Data category	MPG value
Window frames, aluminum coated	N/a	Cat 3	0,01
Glazing HR++	N/a	Cat 3	0,041
Window sills fiber cement	250 mm; 10mm	Cat 3	0,001
Window frames, recycled PVC	N/a	Cat 3	0,004
Sandwich panels	42 mm	Cat 3	0,011
Doors aluminum coating	N/a	Cat 2	0
			0,067

Table 41 Window composition as in MPG, current state

Alternative wood window frames			
Element name	Parameters	Data category	MPG value
Window frames, painted wood	N/a	Cat 3	0,002
Glazing HR++	N/a	Cat 3	0,041
Window sills fiber cement	250 mm; 10mm	Cat 3	0,001
Window frames, painted wood	N/a	Cat 3	0,002
Sandwich panels	42 mm	Cat 3	0,011
Doors painted wood	N/a	Cat 3	0
			0,057

Table 42 Window composition as in MPG, wood alternative

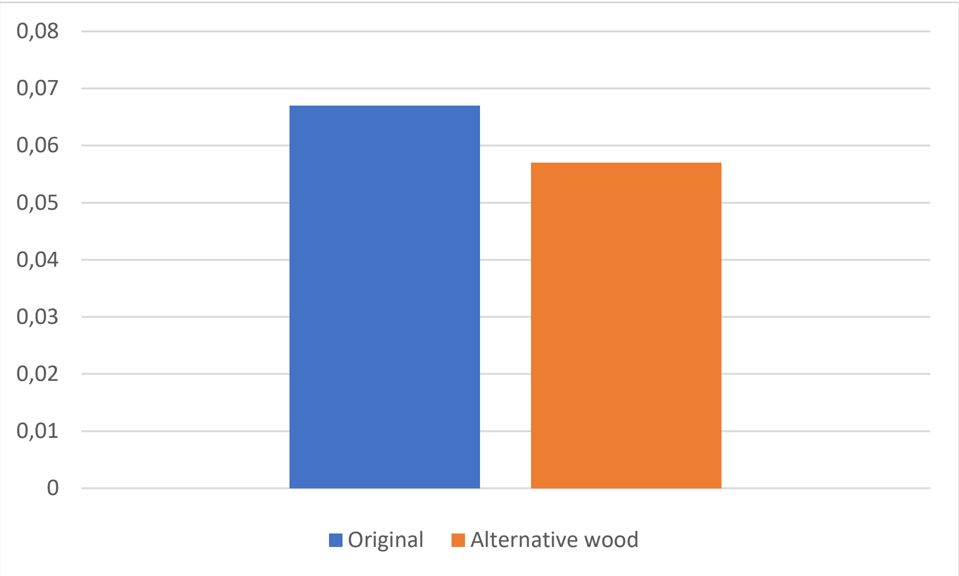


Figure 20 MPG scores of different variants for windows

7.2.5 Closed façade

When comparing the different construction methods as done earlier in this research, the closed façade of this building finished with pinewood has a low environmental impact, see Table 43. However, when looking at the NMD, Meranti has been shown to lead to an even lower score. In fact, the impact of Meranti is 80% lower. The environmental impact is lower because this alternative needs less maintenance. That is important to note as the energy needed for producing this hardwood will likely be higher then for pine wood. However, this will not significantly affect the whole MPG as the closed façade makes up only 5% of the entire calculation. The total MPG as shown in part 5.11 is decreased with 2%.

	Traditional construction	**Modular construction**	**Panelized construction**
	Brickwork	Pine wood	Moso Bamboo Extreme
MPG score	0,008	0,005	0,039

Table 43 MPG scores of different facade finishings in different cases (outcome heavily affected by shape building)

Original façade finishings			
Pine wood	N/a	Cat 3	0,005
			0,005

Table 44 Facade finishing as in MPG, current setup

Alternative meranti finishings			
Meranti wood	N/a	Cat 3	0,001
			0,001

Table 45 Facade finishing as in MPG, meranti alternative

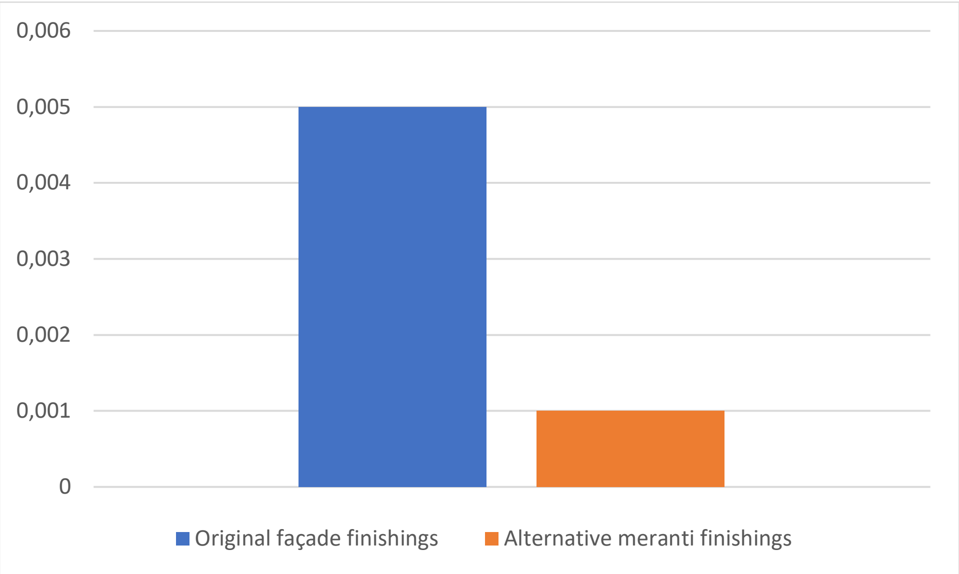


Figure 21 MPG scores of different variants for façade finishings

7.2.6 Conclusion strategy 2: Choosing different materials

This strategy has shown to be effective in the case of this project using modular offsite construction. It is probably also possible to apply this strategy for other types of construction using the same methodology.

7.3 Use more cat 1 or 2 data

It would be beneficial to steer towards more category 1 data. However, the NMD still works with a lot of category 2 and 3 data. To find options to lower the MPG in this case the top 4 elements shown in Table 46 will be evaluated.

The top 4 elements significantly impact the MPG score and will therefore be assessed in this part. Alternatives will be searched to replace these cat 3 data with elements with cat 2 or 1 data.

Table 46 Inventory category 3 data modular case

Name	Element	Category	MPG value
HR++ glass	**Open façade**	**3**	**0,041**
Closed window elements	**Open façade**	**3**	**0,011**
Aluminum window frames	**Open façade**	**3**	**0,01**
Interior door frame steel	**Inner walls**	**3**	**0,009**
Timber frame element	Closed façade	3	0,005
Pine façade finishing	Closed façade	3	0,005
PVC window frames	Open façade	3	0,004
Suspended ceiling frame	Floors	3	0,002
Stairs	Stairs	3	0,002
Interior door frame wood	Inner walls	3	0,001
Windowsill	Open façade	3	0,001
Sand	Foundation	3	0
Interior door wood	Inner walls	3	0

7.3.1 HR++ glass

In the current setup 1.115 m^2 of insulated glazing is used leading to an MPG of 0,041. There is however an alternative available in the database to reduce this with 44%. Although it is not in the element's name, the option is also an Aragon-filled glazing system (AGC Glass Europe, 2019). The total MPG as shown in part 5.11 is decreased with 7%.

Original glazing			
HR++ insulated glazing coated	N/a	Cat 3	0,041
			0,041

Table 47 Glazing as in MPG, current setup

Alternative glazing			
HR++ insulated glazing uncoated	N/a	Cat 2	0,023
Coating insulated glazing	N/a	Cat 2	0
			0,023

Table 48 Glazing as in MPG, alternative

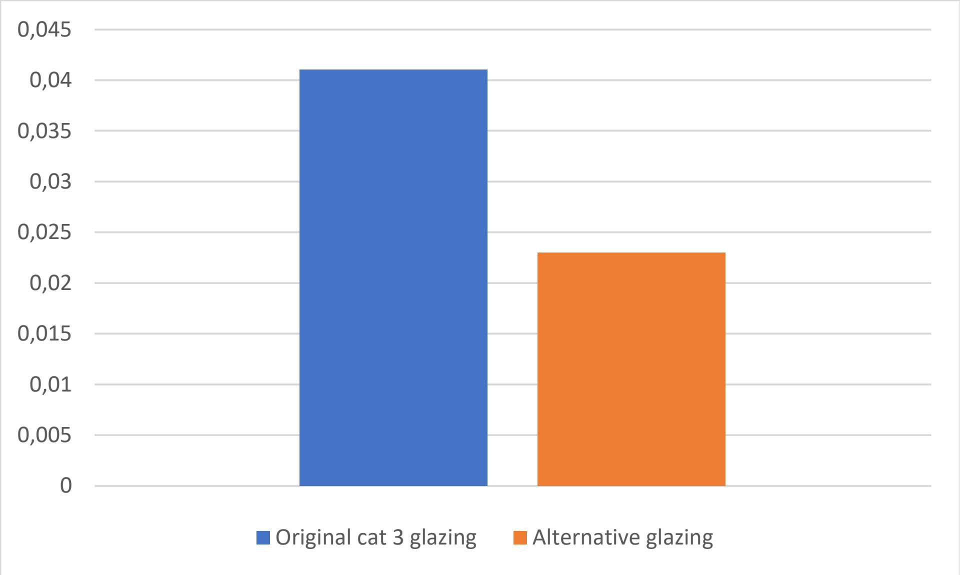


Figure 22 MPG scores of different variants for glazing

7.3.2 Closed window elements

The current database has no better alternative for the current setup.

7.3.3 Aluminum window frames

The current database has no better alternative for the current setup. However, opting for another material shown earlier in this chapter has proven to be effective in lowering MPG.

7.3.4 Interior door frame steel

The current database has no better alternative for the current setup. However, opting for another material shown earlier in this chapter has proven to be effective in lowering MPG.

7.3.5 Conclusion strategy 3: Use more cat 1 or 2 data

This method was proven viable and effective for the modular case of Leerpark. This was however only possible for one element. Nonetheless, it is likely that this strategy is also applicable for other cases.

7.4 Enter a longer lifespan for a building

Looking at the guidelines for entering a longer lifespan into the MPG calculation it would be possible to obtain a bonus as shown in Table 49. When using this longer lifespan in the MPG calculation the MPG will decrease by 17% as shown in Table 50.

This calculation can be filled in for all cases with different outcomes. Therefore, the effectivity of this strategy strongly depends on the characteristics of the case and this strategy might not be effective for all construction methods.

Calculation tool					
Max bonus	100%				
Use	Residential				
Characteristic	Option	Score	%	Factor	Bonus
Building quality			50%		0,0%
Robustness			60%		0,0%
Robustness design	Standard	0	70%	21%	0,0%
Futureproof construction	Standard	0	30%	9%	0,0%
Identitiy			40%		0,0%
Aesthetic	Standard	0	80%	16%	0,0%
Landmark	Standard	0	20%	4%	0,0%
Adaptability			50%		20,7%
Building volume			20%		10,0%
Expandability	Excellent	3	80%	8%	8,0%
Decreaseability	Excellent	3	10%	1%	1,0%
Replaceability	Excellent	3	10%	1%	1,0%
Layout within volume			40%		4,0%
Divisibility	Standard	0	40%	8%	0,0%
Adaptability within unit	High	1	60%	12%	4,0%
Services			40%		6,7%
Adaptability technical quality	High	1	70%	14%	4,7%
Expandability services	High	1	30%	6%	2,0%
Total characteristics					20,7%

Conclusion		
Use	Residential	
Default	75	years
Bonus	20,7%	
Final life span	91	years

Table 49 Results guideline longer lifetime in the modular case

	Current	Alternative
MKI	€ 132.842,00	€ 132.842,00
GFA (m²)	6981,6	6981,6
Lifespan (years)	75	91
MPG	0,254	0,209 **(-18%)**

Table 50 Difference in MPG when entering different lifespans in modular case

7.5 Conclusion

This part was written to answer the following question:

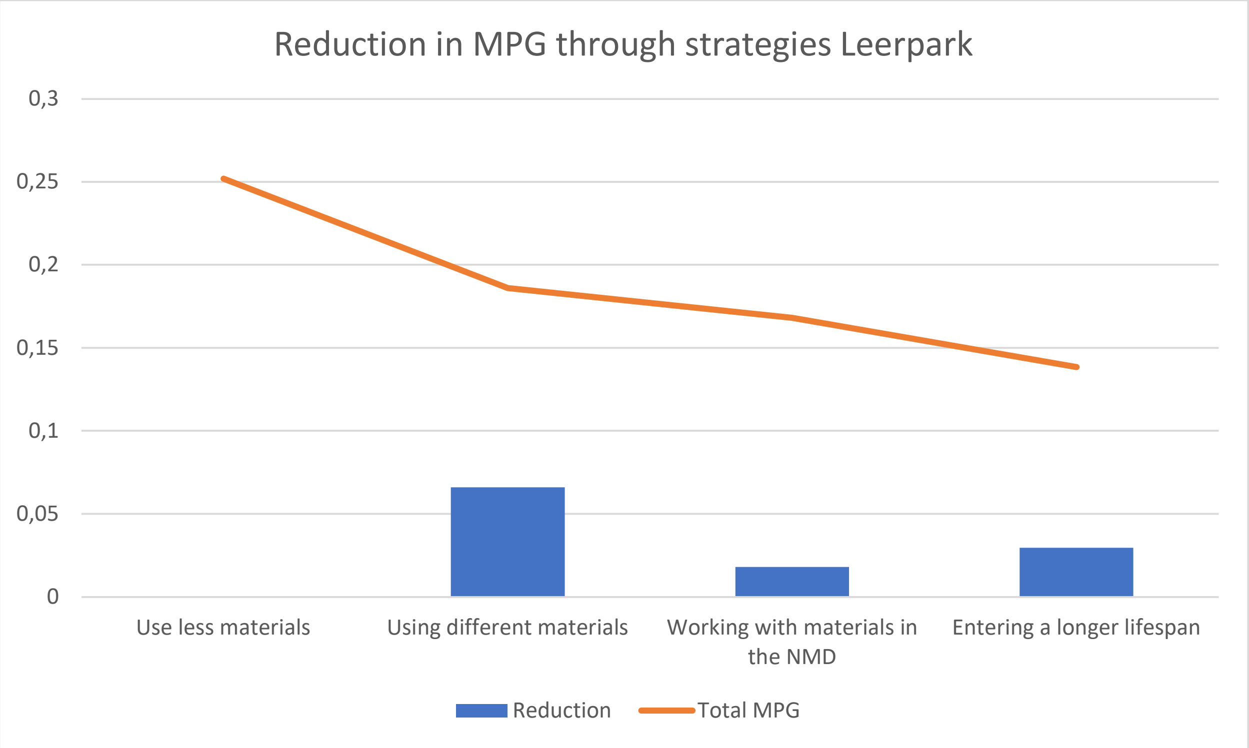
What are the possibilities for Daiwa Modular House Europe to reduce the environmental impact of their project Leerpark Dordrecht with 25%?

The answer is in line with the conclusions of chapter 6 and consists of three main strategies

1. Using different materials
2. Working with materials registered in the NMD
3. Entering a longer lifespan

The first strategy would lead to a reduction of 0,066 on the MPG.
The second strategy could lead to a reduction of 0,018 on the MPG.
The third strategy leads to a reduction of 0,030 on the MPG after implementing the first two strategies.

This set does lead to a total reduction of 29%.



It is remarkable that of the four strategies from chapter 6 only two strategies will result in a lower environmental impact. This means that the MPG has some limitations in assessing buildings on their environmental impact. This will be discussed in the next chapter.

8 Limitations of the MPG

In this chapter, the limitations of the MPG will be discussed, answering the question:

What are the limitations of the MPG in comparing different construction methods?

The previous chapters have shown that the MPG is limited in its scope and extensiveness on the environmental impact assessment. This chapter will highlight these limitations. First, through literature study the discussion about the limitations of the MPG in the Netherlands is researched. Then several limitations of the MPG are found which are then validated. First, a list of limitations is made, which is then validated through the interviews. This is done through semi-structured interviews. Four semi-structured interviews were conducted to find whether there were more limitations and to validate the already found limitations. The four interviewees work at companies that either research the environmental impact assessment or use these environmental impact assessments on a daily basis. The specific professionals are all very familiar with the impact assessment.

8.1 Critique on the MPG

There have been several appeals for improvements to the MPG (Gideons tribe, 2022; Korbee, 2022; Oostdijk et al., n.d.; TNO, 2021; Transitieteam Circulaire Bouweconomie, 2018).

The first appeals started after the Transitie Agenda Circulaire bouw. This was an initiative from a team of science, government and market parties experts. It was initiated to describe a strategy for a circular construction economy in 2050 in line with the goals of the Dutch government to be circular in 2050. According to their findings, a system is needed to measure circularity in the built environment possibly using an updated version of the MPG. Furthermore, the team indicated that the MPG system would have to be extended with the possibility to display the reusability of elements and a uniform assessment for all buildings and renovations (Transitieteam Circulaire Bouweconomie, 2018).

This led to the research undertaken by Berenschot commissioned by the Dutch government to assess whether the NMD/MPG system is sufficiently robust and effective to fulfill its role in accelerating the transition to a circular construction economy. This research showed that the system is working but could use some updates. Especially the lack of EPD’s in the NMD was seen as a problem. Also, the non-committal nature of the system as almost all buildings pass the maximum value is compromising its effectiveness. Lastly, the lack of enforcement does not enhance effectiveness (Oostdijk et al., n.d.).

Later in 2020 a group of construction companies, developers, clients, architects and consultants showed their discontent and have signed the manifesto "A level playing field for a more sustainable Netherlands’’ (Diersen, 2020). The impetus for this was an article by Van der Lugt en Van Leeuwen on the limitations of the MPG. The core message of this manifesto was that CO_2 sequestration through biomaterials was not correctly considered in the MPG calculation. Therefore, the signers asked politicians and policymakers to include CO_2 storage in the MPG calculation instruments to create a level playing field for biobased materials that will enable a sustainability drive.

This manifesto led to attention in politics and parliamentary questions. Dutch research institute TNO analyzed the consequences if the temporary sequestration of biogenic carbon were to be valued in the MPG calculation. The research showed that if carbon sequestration in wood structures were to be included, there would be a net reduction of 50% in global warming impact compared to the scenario that does not include temporary CO_2 sequestration. This would mean that wood structures would outperform concrete by far in MPG calculations. In specific projects, wood CLT structures would even lead to a negative global warming impact as more CO_2 would be stored in the whole lifecycle of the building than needed when constructing the building (TNO, 2021).

After the manifesto, questions were raised in the House of Representatives to the Minister of the Interior and Kingdom Relations. In response to these questions, the minister indicated that he would propose how the valuation of the environmental impact of the temporary storage of CO_2 in bio-based materials, including wood, could be incorporated into the MPG system. SGS Search has been commissioned to develop a methodology that allows for the valuation of the amount of carbon sequestered in biobased building materials. SGS Search worked out a methodology in which it is possible to value the carbon captured in building materials by calculating this after stage A3 and again for the possible reuse of the element (Ministerie van Algemene Zaken, 2022).

However, no immediate action was undertaken by the Dutch government, leading to another manifesto similar to the prior one. This one was called Manifesto 2.0: Building within the limits of our planet. The initiators were also the group behind the first manifesto and now work together under the name Gideons. The new manifesto has three main points (Gideon, 2022b):

1. The introduction of an "MPG-2", which focuses on environmental impacts in the production and construction phases.
2. Improving the Environmental Performance System as a whole
3. Defining a carbon budget for the construction sector, to set a limit on the sector's total CO_2 emissions

There were no further developments in this field at the time of doing this research. However, there have been topics found in literature and the prior comparison and topics came up in the interviews with experts as well, showing the importance of these specific issues.

8.2 Limitations in the material based approach

Looking at the findings from prior chapters, it is evident that the MPG only assesses the materials used in the buildings. Looking at the construction materials opposed to the design as a whole has consequences for the end result of the calculations. Especially in combination with the database which only allows for the selection of materials without adapting travel distances or way of mounting these materials. This can be seen in Figure 23 and Figure 24. These two figures show how you would enter the poured concrete floors used in the modular building and in the traditional building. Entering these elements is the same for both construction methods, choosing the right material from the list (Figure 23) and entering the right thickness and surface area afterward (Figure 24). Therefore, it is impossible to enter the travel distance for the different projects and the spilling numbers, which are likely to be lower in offsite construction (Kozlovská, 2011).

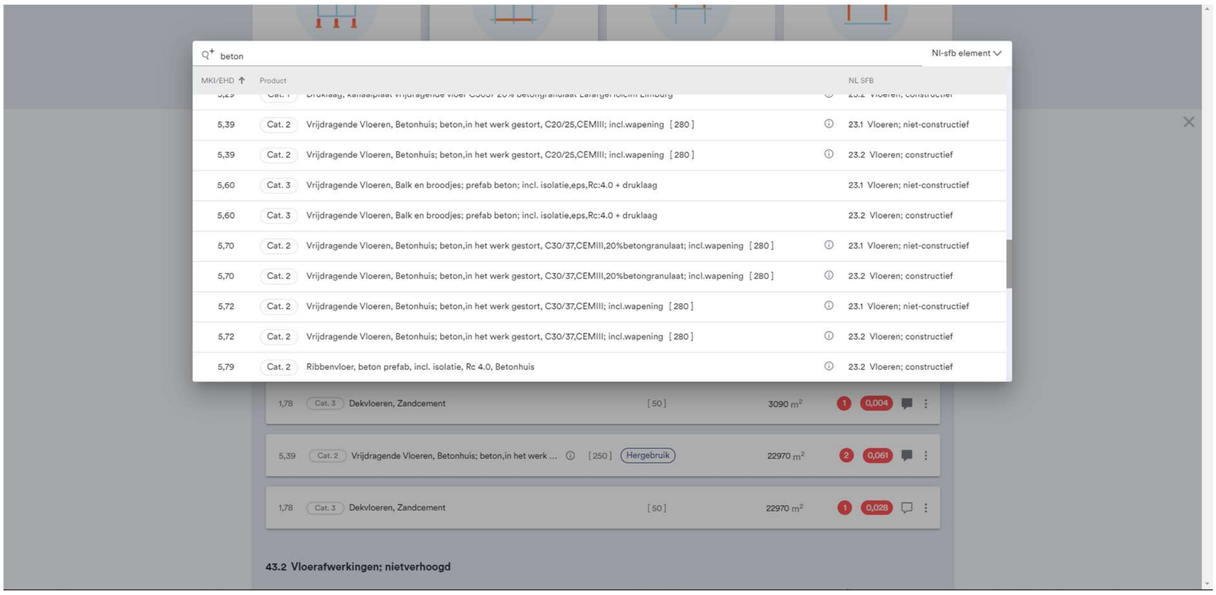


Figure 23 Screenshot GPR MPG tool

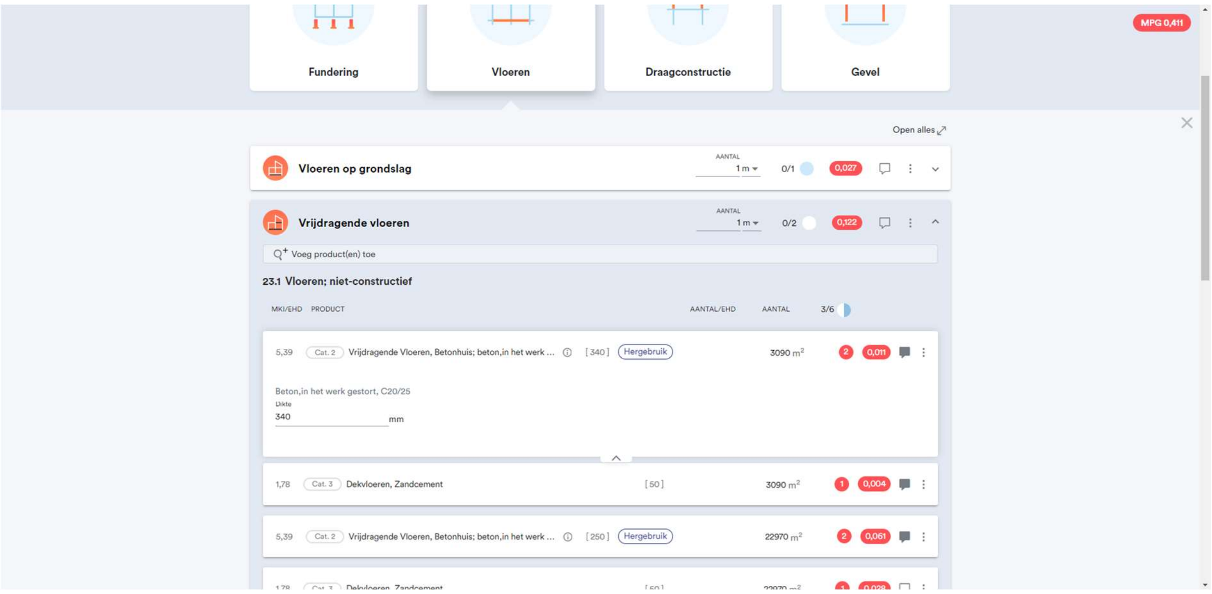


Figure 24 Screenshot GPR MPG tool

The material-based approach is also currently not well suited to consider the possibilities for disassembly of the different construction methods as the comparison showed and was validated in an interview (Anonymous interviewee, personal communication, October 26, 2022). In the case of the panelized construction method, the supplier indicated that the walls would be connected to allow for dismantling and reusing the elements. However, looking at the GPR tool in Figure 25 it is only possible to select the material and the quantity. The CLT sector could have supplied an EPD in which a scenario is included for reuse of CLT panels. However when reading the EPD the inner wall elements are not marked as reusable but even as bio fuel for energy plants, meaning that the elements will be burned after demolishing the building (Nederlandse Branchevereniging voor de Timmerindustrie, 2016). This has led to a higher environmental impact than when it would be reused in another building.

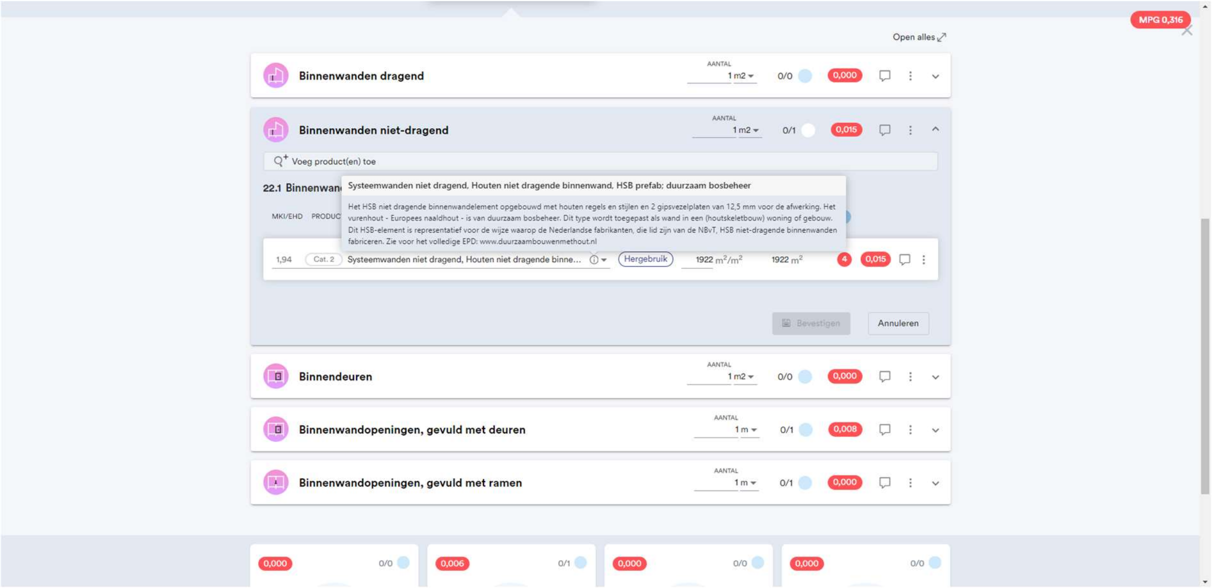


Figure 25 Screenshot GPR tool wood wall element

8.3 Limitations in the NMD

This last point also shows the shortcomings of the NMD. Not all suppliers submitted information of their products. When the specific product is not in the database category 3 data has to be chosen which is less accurate and is higher than category 2 or 1 data supplied by a manufacturer. In fact there is a multiplication factor of 30% for category 3 data (Stichting Nationale Milieudatabase, 2022). This leads to different outcomes of the MPG when choosing elements of different makes even though the elements would be made from the same materials (Anonymous interviewee, personal communication, October 26, 2022; DGBC, personal communication, October 18, 2022; W. Kuijper, personal communication, October 24, 2022). This can be related to the high costs of entering materials into the NMD. However, LCA software tools are developed allowing bulk LCA verification. This brings down the costs of LCA verification + NMD uploading per product. The overall costs are the same for one separate product as for five hundred products. However, this advantage is smaller for startups with a smaller product portfolio. (I. Bak, personal communication, November 21, 2022).

This is also the case when comparing the interior doors chosen in the modular and panelized buildings. The panelized building comes with doors of a supplier that did not upload its data to the NMD. Therefore, category 3 doors are selected leading to an MPG of 0,008 for ten doors, as shown in Figure 26. Figure 27 on the other hand shows that the modular building comes with doors from a manufacturer that uploaded data about its product in the NMD. This category 1 data combined with category 3 data for the door frames leads to an MPG of 0,004 for ten doors, half of the selection of the panelized building.

Figure 26 Screenshot of the GPR MPG tool for the interior doors of the panelized building

Figure 27 Screenshot of the GPR MPG tool for the interior doors of the modular building

Overall, the system is very dependent on the availability of product sheets in the NMD. If all suppliers specified their products in the NMD it would be highly likely that the environmental impact according to the MPG will be a lot lower for many buildings.

This was also the case when W/E adviseurs did a comparative MPG research when there were not as many EPD's available for wooden construction elements. Because they had to use more category 3 data, they concluded that the wooden buildings' MPG scores would probably be lower if more cat 2 and 1 data were available (van der Veen & Hemelaar, 2022.

Not submitting cat 1 data can also be done on purpose. One interviewee added that some sectors opt for category 2 data for a sector to avoid competition between members based on their MPG scores (W. Kuijper, personal communication, October 24, 2022). This undermines the reliability of the MPG calculation as a whole.

8.4 MPG vs Energetic performance

There has been discussion about the interplay between the MPG and the energy performance labels of buildings (Alsema et al., 2016; Korbee, 2022; Nijman, 2019; W/E Adviseurs, 2021). The energy performance of buildings is often enhanced by using building elements that negatively impact the MPG, like solar panels or insulation panels (Anonymous interviewee, personal communication, October 26, 2022; Dutch Green Building Council, 2022; W. Kuijper, personal communication, October 24, 2022; van der Veen & Hemelaar, 2022).

There have been initiatives to combine tools for resource effiency of buildings and energetic performance. Alsema et al (2016) worked towards integrating the MPG and buildings' energetic performance into one assessment. Nijman (2019) assessed several façade designs using an integrated sustainability assessment based of the MPG and EPG showing how difficult it is to find an optimum between the two.

One interviewee gave a specific example in which a contractor expected to obtain a super low MPG score as he deliberately chose materials with low embodied energy. However, as this contractor also aimed for an energy-efficient building in the use phase, the MPG score did not turn out to be as low as expected (Anonymous interviewee, personal communication, October 26, 2022).

8.5 Long timespan

Two interviewees indicated that a better method to assess the environmental impact of buildings could be to look into the carbon emissions of the production and construction stage (Anonymous interviewee, personal communication, October 26, 2022; DGBC, personal communication, October 18, 2022). This would help to reduce carbon emissions now rather than in the long run with the current system were emissions from current actions are spread over the lifespan of a building (default 75 years).

Also, there is a lot of uncertainty when making scenario's for a future 75 years from now.

This idea can also be seen in the arguments for a carbon budget but it is also used in the EU policy of Levels (European Commission, 2021).

8.6 Biobased materials

An important issue already indicated in this chapter's beginning was the assessment of biobased materials. Several researchers showed that there would be different options to measure the environmental impact of biobased different to ensure that their score in the MPG is fair (Fraanje, Nijman, et al., 2021; Ministerie van Algemene Zaken, 2022).

The interviewees confirmed this issue. However, one of the interviewees indicated that the branche as a whole can solve this as this happened before. This happened with EPS insulation which was not recycled at the end of its life at first, but through action of the branche the NMD changed the default values for recycling of EPS to 80% (I. Bak, personal communication, November 21, 2022). Unfortunately, the branche organizations of biobased materials haven proven to be not as active as the organizations of more traditional building materials (Anonymous interviewee, personal communication, October 26, 2022; DGBC, personal communication, October 18, 2022)

8.7 Conclusion limitations

This chapter aimed to answer the following question:

What are the limitations of the MPG in comparing different construction methods?

The answer concentrates on five main topics from literature, interviews and earlier research findings.

1. The material based approach
   This does not allow to take the design as a whole into account. Therefore it is impossible to take factors such as prefabrication or dismantling possibilies into account.
2. The limited NMD
   There are not enough cat 1 or 2 items available in the NMD. When the specific product is not in the database category 3 data has to be chosen which is less accurate and comes with a multiplication factor of 1.3. This leads to different outcomes of the MPG when selecting elements of different makes even though the elements would be made from the same materials
3. MPG vs energetic performance
   The energy performance of buildings is often enhanced by using building elements that negatively impact the MPG, like solar panels or insulation panels. As designers with a focus on sustainability often look into sustainable materials and low energy use, the MPG often leads to a higher score than a building without any sustainable guidelines.
4. Long timespan
   The MPG does not help lower construction emissions now as the embodied energy is spread over 75 years. Measuring the current carbon emissions would help to reduce carbon emissions now rather than in the long run with the current system. Further, it is hard to establish end-of-life scenarios for the future 75 years from now.
5. Biobased materials
   Biobased materials are not fairly assessed in the current system. For example, the low energy needed to make these materials are not recognized in the current MPG as carbon

sequestration is not measured. Therefore these materials get a worse score than one might expect.

9 Discussion

This chapter summarizes and interprets the key findings of this research. Also, limitations of this research are acknowledged.

9.1 Typologies within offsite construction

Chapter 2 showed that there are various typologies for offsite construction within literature. Three different typologies were presented: one from the work of Gibb (2001), one from the work of Ginigaddara et al. (2019) and one framework made by McKinsey (2019).

It was concluded, that there are two types of offsite construction volumetric or panelized. That is however quite simplistic as the other typologies do not only take shape but also amount of offsite work into account. Also, there may be more research on typologies available in literature but not taken into acount by the researcher. However, the fact that two sources are not older than 5 years indicates that the typologies can still be applied to current construction methods.

For further research, looking into more literature to find a broader distinction between the construction methods could lead to interesting insights.

9.2 Measuring environmental impact

The research showed how the environmental impact of a building could be measured in chapter 3. First, LCA methodologies were explained followed by explanations of the MPG. Then, after looking into other options to measure the environmental impact of buildings it was concluded that the MPG tool was best suited for this research mainly due to the resources needed for the other tools in form of time and input.

It is possible that other options would have been available to better assess the environmental impact of buildings that fit within this research's scope. However, this seems unlikely as several options were tested on their feasibility within the scope of this research.

For further research, the more extensive scope of the other tools would likely lead to different results which would prove relevant to indicate such a tool's effectiveness.

9.3 Differences between construction methods

Chapter 2 concluded that there are 2 types of offsite construction and chapter 3 concluded that the MPG would be the right tool to measure the environmental impact of a building for this research. Therefore in chapter 4, 3 construction methods (the 2 offsite construction methods and 1 onsite construction method) are compared to each other on relevant factors for the MPG. The LCA assesses a lifecycle within different stages and these stages were therefore used to compare the different construction processes of the different construction methods. Building materials were proven to be relevant for the MPG and the most important ones according to NMD were used as a framework to compare the construction methods.

This chapter concluded that there were mainly differences between offsite and onsite construction in the construction and end-of-life stage. For materials there were several differences found in different building elements.

To compare the construction methods three cases were used. To foster comparability the three cases were new or <5 years old but did obtain a building permit. This proved the feasibility of the construction methods. Also, the unit sizes were roughly the same to make sure converting the units into studios would be possible. The cases of the construction methods were used as representative for the 3 construction methods as a whole but there is likely to be a plethora of alternatives that use slightly different construction processes or materials. However, the difference found in the stages was also recognized within literature, making this conclusion more reliable. However, the fact that the two offsite construction cases applied for the MIA/VAMIL subsidies will probably have affected the material use in these cases. However, it was already indicated that the difference in material use would help to test the differences in the environmental impact of different buildings. It remains premature to assume that the material choice in these cases represents the construction method as a whole.

The environmental impact of these cases are not entirely comparable for various reasons. Chapter 4 starts of with various parameters that affect the comparability of the MPG scores. This is a limitation of this research. A comparison with one building engineered in two other construction methods would enable a more robust comparison and would be interesting for future research. Especially, the difference in size, location, construction year and use affected the comparability significantly.

Services and space plan of the cases were left of the assessment. This is an important limitation of this research. Predominantly as 35% of an MPG consists of the impact of installations that are part of services. For this research, the installations were considered fairly similar in each case and were therefore not part of the assessment. However, the installations may be affected by choice of construction method. This is a limitation of this research and should be investigated further in future research.

The research has shown that the end-of-life scenarios for the different construction methods are very different as the offsite cases could be dismantled and rebuilt elsewhere. This research did not look into the environmental impact of the building in its second life cycle. This would be very relevant and interesting for future research.

9.4 Measuring environmental impact

In chapter 5, the MPG's of the three cases were drawn up and compared. This was done by re-entering the MPG's into the newest version of the MPG tool. Then, the results of the MPG's were compared. The conclusion is that the modular building has the best MPG score whereas the traditional building has the worst MPG score. The panelized case is somewhere in between.

The representativeness of the cases for the construction methods can be disputed as shown in 9.3. Further, to enhance comparability the MPG's used in the application for the environmental permit were re-entered into the newest version of the MPG tool used. The data was used from the original MPG's which were all drawn up by different advisors. This could have compromised the reliability of the original data. Nonetheless, the original MPG's all proved to be sufficient for an environmental permit and are in line with the guidelines from the NMD.

For future research, it would be interesting to see whether the results would have been different if the same advisors had made the original MPG's. Also, as the NMD is constantly updated, the MPG score of the same building can likely vary over time as more reliable data comes available. It would be interesting for further research to test this hypothesis.

The MIA/VAMIL subsidy likely affected the material choice of the two offsite cases and thereby the environmental impact. For this research however, the differences in materials helped to show how the environmental impact is affected by material choice.

In the Netherlands new residential buildings are subjected to regulation. There is also regulation on the energy efficiency of buildings. The minimum energy efficiency of buildings has been reduced over time and will continue in the future. The research has shown that the energy efficiency of a building affects the environmental impact of buildings. However, as all new residential buildings are subjected to these requirements an increasing number of buildings will have a comparable energy efficiency. Therefore, when comparing the difference in environmental impact of new buildings, the differing energy efficiencies will be less important for the differences in environmental impact.

9.5 Strategies to lower environmental impact

Strategies to lower the environmental impact of buildings were shown in chapter 6. 4 strategies were identified after looking into the MPG comparison done in this research and in two other comparisons done by other researchers.

The chapter concluded that there are 4 strategies to lower the MPG and 2 of those strategies would also help to lower the environmental impact.

It would be possible that there would be other strategies available in research that were not found within this research. It would be recommended in future research to see whether more literature is available. The research undertaken by Van der Veen and Hemelaar (2022) and DGBC (2022) nonetheless did come with similar conclusions. However, in this specific research the MPG was used to measure the environmental impact based on research in chapter 3. It would be possible to look into researches that used different environmental impact assessments that identified other strategies. In general, other conclusions were likely drawn if another tool had been chosen. Nonetheless, using the MPG has made this research very relevant for the Dutch construction industry. For future research, using another tool could lead to very different outcomes that would be very relevant for science and test the MPG's effectiveness.

Various actors in the construction process's supply and demand chain affect a building's environmental impact. On the demand side, the availability of construction materials provided by suppliers will have an effect. The demand side also has a variety of different actors affecting the environmental impact of a building. The client for example might prefer a concrete building over a wooden building for their own reasons. Also, factors like future value, functionality, cost and durability will affect the design of a building and thereby the environmental impact of a building. This was not explored in this research but would be important to consider when assessing the environmental impact.

9.6 Strategies to lower environmental impact in practice

Within chapter 7 the 4 strategies from the chapter before are tested on its viability and effectiveness through a case. This was done by working on recommendations that were tested on their viability by interviewing an employee of Daiwa.

It was concluded that implementing the first strategy was not possible but that the other 3 strategies together could lead to a reduction of 29% for the MPG made in this research for the case.

There were possibly more options available that were not recognized in this research. Nonetheless, the interviewee has much experience on this subject and was able to give many options. Interviewing more experts could have led to another number of solutions as more or fewer suggestions would have been recognized as viable. This could be interesting for future research. Nonetheless, using the combination of this chapter and the chapter before did allow to sketch a reliable insight into the possibilities to lower the MPG and environmental impact.

9.7 Limitations of the MPG

By looking into literature and the comparison of this research several limitations of the MPG were identified. Then, by interviewing experts, these limitations were validated. Also, these interviews enabled the researcher to find other limitations not identified in literature.

This chapter concluded that there are 5 main limitations to the MPG:

- Material based approach
- The limitations of the NMD
- MPG vs. energetic performance
- Long timespan
- Biobased materials

This research method has allowed for a broad insight into the public discussion around the MPG. Especially the validity and completeness is likely to be high due to this combined research method of literature study, assessing the MPG after using it and interviews. However, directly comparing the MPG tools to alternatives for future research would be interesting. This could show the advantages and disadvantages of the tools directly.

10 Conclusion

This research aimed to find out whether offsite construction is more environmentally sustainable than onsite construction and how the environmental impact of offsite construction can be reduced. Using a case study of three different construction methods and the MPG as a tool to calculate environmental impact, it was found that offsite construction resulted in buildings with a lower environmental impact. Subsequently, four strategies were identified to lower the MPG of a building. Two of these strategies would also lower the environmental impact. This conclusion was drawn after first answering the sub-questions.

What are the different typologies within offsite construction?

Research is not conclusive on typologies within offsite construction. They use different approaches to create distinctions and contradict one another in various fields. The one thing they do have in common is that different typologies all take the shape of the offsite-produced elements into account. The two most relevant types of offsite construction are 3D modular construction and 2D panelized construction. These were likely to differ in environmental impact due to different logistics and were therefore compared in this research.

How can the environmental impact of buildings be measured?

There are different methods to assess buildings on their environmental impact. The MPG showed to be the most feasible option for this research. This calculation is needed when you apply for a building permit and is therefore made for every new building in the Netherlands. The MPG shows the environmental impact of the materials used in a building.

What are the differences between offsite and onsite construction regarding construction processes and used materials?

Subsequently, the different construction methods assessed in this research were compared: onsite construction, modular offsite construction and panelized offsite construction by using case studies for each construction method. The offsite construction methods work with extra steps in the construction stage for offsite assembly of building elements and transport of elements to site. Also, the end-of-life stage for the offsite construction methods was different as these buildings can be dismantled and rebuilt. This will likely affect the environmental impact.

How does the environmental impact differ between offsite and onsite construction methods?

Unfortunately, when comparing the environmental impacts of the buildings, these differences were not assessed in the MPG calculation. Nonetheless, the two offsite construction cases got a better score on the MPG than the traditional case, showing that the environmental impact of offsite construction is lower. The lowest MPG score was for the modular project and the highest for the onsite case.

How can contractors of off-site construction steer towards a lower environmental impact of their industrialized construction methods and housing products?

This made it possible to find the answer to the main question. Four different methods exist to lower the MPG of an offsite constructed building. Two of these strategies would also help to bring down the environmental impact.

To bring down the environmental impact:

1. Limiting the use of materials

2. Choosing different materials

To bring down the MPG score:

3. Use more cat 1 or 2 data
4. Enter a longer lifespan for a building

The first two options would help to decrease the energy needed to source materials and thereby the environmental impact of the building. The most obvious choice would seem to be to use less materials. Another option would be to use other materials. For example, biobased materials like wood could lead to a lower environmental impact.

The other two options would not affect the offsite construction methods as much and are more related to making better use of the possibilities within the MPG. The first option would be to use other data available within the NMD. The second option would be making use of a guideline that assesses a building on its building quality and adaptiveness.

Implementing these four strategies in the case of a modular offsite produced building in the Netherlands would reduce 29% on the MPG. Although strategy 1 was not possible in this specific case, the other 3 strategies proved viable and effective.

What are the limitations of the MPG in comparing different construction methods?

However, there are limitations within the MPG to compare buildings on their environmental impact. The MPG only considers the materials of a building and not the construction method or the building as a whole. For example, offsite construction has been shown to lead to less spilling and better reuse possibilities but this is not assessed within the MPG because of the material-based approach. It would be possible to use the guidelines for the robustness and adaptability of a building to get a better score in the MPG but this is rarely used and does not seem to be a viable method to assess a building as a whole.

Also, the NMD is incomplete. Not enough category 1 or 2 data are available to compare the environmental impacts of buildings. This affects the representativeness of the MPG. Also, this allows room for interpretation by an advisor drafting an MPG. Therefore, using strategy 3, an advisor can get a better score for a building.

Further, the MPG conflicts with energy-efficient design choices that could help bring the total carbon emissions down of a building throughout its lifespan. Also, the long timespan that is taken into account for buildings in the MPG is comprising its reliability. Predictions about the future end-of-life scenarios are 75 years from now which are hard to forecast. Lastly, biobased materials are not fairly assessed in the current system. For example, the low energy needed to make these materials are not recognized in the current MPG as carbon sequestration is not measured.

11 Recommendations

In this section, recommendations are presented for practice and research based on the findings of this research.

11.1 Future research

The MPG and measuring the environmental impact of buildings is more important than ever and more research is needed into this topic. The MPG for example is selected as a policy instrument to bring down the environmental impact of buildings but it has its limitations. Future research into these limitations and avoiding them is very important. Especially, the dismantle possibilitied, limited scope of the NMD and biobased materials are beneficial factors for the current system's reliability. Also, there are numerous tools available to measure the environmental of a building. It would be very insightful to test how the results differ of these tools when assessing the same set of buildings. Lastly, the NMD is constantly updated and more materials are available each year. Performing this exact research three years from now could lead to different outcomes showing the current system's limitations.

11.2 Practice

First of all, it is recommended for contractors to implement the four strategies to lower the environmental impact. Especially, the first two are very relevant. Although biobased materials are currently not that much better for the environment according to the MPG these materials may be assessed very different a few years from now in the MPG. Secondly, clients that want to achieve a building with a low environmental impact are recommended to look into the limitations of the MPG as shown before. Also, the four strategies to lower the environmental impact show that the MPG can be confusing and can be lowered relatively easy without adapting the buildings' design. In fact, it is recommended to use a different environmental impact assessment with a broader scope in tenders. If working with the MPG after all, knowing the limitations of the MPG is very important. Lastly, policy makers are recommended to collaborate with professionals familiar with the MPG to work towards an updated MPG. This research has shown that there are limitations to the MPG and that comparing buildings with the MPG is difficult. Some research has been published to assess biobased materials for example fairly. Research like this could be implemented in the MPG. Also, the NMD is currently a weak link in the current system. Allthough, it makes sense to work with a party like the NMD, in its current form, it is difficult for suppliers to enter their materials into the NMD. Working with more subsidies and more investments in the NMD could help.

12 Reflection

In this section I reflect upon the choice of method for this research, whether this was effective and my personal reflection. Also, the relation between my master track and graduation topic will be discussed.

First of all, choosing this topic was quite challenging, leading to a complicated process of picking and rejecting various topics. My strategy was to figure out what topics sparked my interest and whether I would be motivated enough to study this topic for a half year. In hindsight, I would have tried to speak with a lot more people, especially with professionals from practice. This would have resulted in a better view of exciting topics and more insider (tacit) knowledge of a topic. This was a challenge when I started my research and quickly discovered that several professionals admitted that the MPG might not have been the best tool for this comparison. However, in the end I do think that this has made my research very relevant for the field. Also, I think that it is essential that this knowledge is now brought into the scientific field through this thesis. On a more personal level this challenge also provided me with some lessons. Especially, as I do not like to ask for help and prefer to work things out on my own. This challenge has taught me to seek help earlier as it will save me much time. But also, most people are willing to help and the result becomes so much better.

Secondly, finding and contacting participants for the cases and interviews was harder than I had anticipated. Initially, my approach was to mail or cold call several interesting parties I had found on the internet. Unfortunately, this first approach did not work out. Then I tried to find participants through old and new colleagues. This approach was a lot more effective. This taught me that my network is much more valuable than I expected it to be. Again, this also showed that many people are glad to help you if you just find the courage to ask. A crucial lesson that I will remember.

Also, dealing with feedback has been very challenging. Especially after the summer break when I figured that the feedback on the P2 presentation would result in an all-new research outline. I was late to figure this out and will ensure that I better understand the implications of feedback earlier in the future. This has made dealing with feedback challenging as this new research outline was confusing for my two mentors and me. Ensuring that my mentors knew the implications of their own feedback is an essential task for a student and I found it very challenging. Although, I do think that I have gotten better at this during this research. I am better at communicating now than I was at the beginning of this research. Especially, after I saw how confusing my presentations and feedback sessions became when I did not communicate my thought process beforehand.

This topic on the other hand has shown to be much broader than I recognized initially. Also, this topic was more intertwined with my field of study than I experienced in the beginning of this research. At the start, I was mostly concerned with the technical details of the buildings and the material quantity. However, later in this thesis the focus moved toward interpreting the MPG and questioning its results. This led to a broader view of measuring the environmental impact of construction. Through this combination of the specific analysis of MPG results and a relation to a broader discussion around measuring environmental impact and the effectiveness of the MPG system as a whole this research would be well placed within the broad field of management in the built environment. Also, the findings of this research can be transferred to other researches looking into different construction methods and researches focusing on the implementation of tools to measure environmental impact. Along the way I figured out that this interplay between the more technical aspects and the broader view on construction suits my personal interest. This was an important and valuable lesson for the start of my career.

The research method that I have chosen could have been better in hindsight. Focusing on more similar cases or remodeling one building into two other methods would have been more logical and would have led to an easier comparison. On the other hand, focusing on three different cases led to a reliable insight in practice, leading to more relevant research. Also, this would not have been viable in this timespan. The MPG turned out to be not a very good tool to measure the environmental impact of different construction methods but I do think that this led to a fascinating discussion and good insights into policies on sustainability.

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Appendices

Appendix A: Validation MPG calculations

Appendix B: Interview data