Research rapport

CO_2 emissions and energy consumption during the construction of concrete structures

Comparison between prefab and insitu concrete viaducts

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COLOPHON

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PREFACE

This report is the result of a research on the emissions of CO_2 and energy consumption in the production and construction of prefab concrete viaducts. This report marks the end of my study civil engineering at the University of Technology in Delft. The research is carried out in cooperation with Heijmans Beton- en Waterbouw.

Numerous people have contributed to this research. I would like to thank my assessment committee of the TU Delft; Hennes de Ridder, Michiel Haas and Gerard. Arends for their feedback and the research. A special thanks to Vincent van Waal, from Heijmans Beton- en Waterbouw, for guiding me in the process and for the advice on the topic. Furthermore I would like to thank all employees of Heijmans who have helped me gathering information for my research and my fellow graduates at Heijmans Beton- en Waterbouw for the nice atmosphere in the room. Special thanks to my parents for their support during my study, both financially as mentally. Finally I would like to thank my girl friend Josanne, for her support both mentally as with respect to the content.

With completing this report I will finish the student years I had in Delft. A period in my life which taught me a lot both on a technical level as well as a personal level. I'm looking forward to my new job and my career as civil engineer.

Coen van Gorkum

Rosmalen, november2010

SUMMARY

Introduction

Contractors and clients in the construction industry are increasingly interested in possibilities to reduce CO_2 emissions and energy consumption. In the civil engineering industry most CO_2 emissions are due to the production of construction materials and construction of a structure. The research focuses on the differences between insitu and prefab concrete construction and whether or not there is a significant difference in energy consumption and CO_2 emission between the two construction processes. The research will cover the entire production and construction process; from the winning of the primary material to the delivery of the structure.

Quick scan tool

To determine and quantify the differences between the two construction methods a tool is developed, called the quick scan tool (QST). This tool is focussed on the construction of a viaduct. The QST defines four elements in a viaduct: Deck/beams, columns, abutments and foundation. There are 5 construction methods defined to nuance the results of the tool. From insitu construction in its most basic form, to fully automated produced prefab elements. With the definition of each construction method, calculation values are appointed. Emissions factors are gathered from multiple sources. The production and construction process is divided in four phases of emissions: Material, transport, factory and onsite.

Results

The QST shows that reductions in CO_2 emissions and energy consumption are possible when constructing with prefab. The reductions originate from three sources. 1) Prefab structures are constructed with high strength concrete (C53/C65), therefore less construction material is required. Due to the reduction of construction material less CO_2 is emitted. 2) The process of prefab construction is more efficient than insitu. Especially the emissions onsite are reduced, because less equipment is required onsite and project time is shorter. The emissions due to transport, will in general, be higher. 3) A prefab deck is constructed with box beams, this results in less force on other load bearing elements and reduces their size. All comparisons in the research are made to “the worst-case scenario”, a predefined case which is an insitu concrete structure, constructed with the least environmental friendly electricity. With prefab concrete construction a total reduction of 23% can be obtained in comparison to “the worst-case scenario”.

Sensitivity analysis

The sensitivity analysis shows there are a number of possibilities to reduce the energy consumption and CO_2 emission of a project. Reducing construction weight and reducing construction material have the most significant influence on the emissions of a project. The implementation of green electricity in factories and onsite is one of the easiest ways to reduce CO_2 emissions, especially combined with the implementation of (electrical) tower cranes. Especially with prefab construction optimizing transport routes is beneficial. Other CO_2 reducing measures, like carpooling or hybrid cars have less effect on the CO_2 emission of a project. The influence of each of these measures on the energy consumption and CO_2 emission of a project depends on the type of construction method which is researched.

Discussion

The results of the tool should be put in the right perspective, due to considerable differences in calculation values and emission factors found in literature. These differences originate from differences in; scope, used data and assumptions. Due to the great array of data used by research institutes the data is difficult to assess.

Future

Construction companies have a number of tools at their dispense to reduce CO_2 emissions in construction industry. Constructing light, reducing the quantity of construction material and utilizing the more efficient process of prefab construction are the most important. Other more well-known options like using green electricity and carpooling have less impact. To which extend construction companies are going to implement these measures depends on how the matter is incorporated in tenders. Governments have two possibilities to reduce CO_2 emissions on a project level. A maximum CO_2 emission can be defined or companies could get reimbursed by reducing CO_2 emissions. The willingness of the government to tackle environmental problems is important in this matter.

CONTENT

INTRODUCTION

In recent years awareness of human impact on global climate change has grown. This concern for the environment has had its influence on the construction industry. Construction companies are more and more challenged to come up with more environmentally friendly ways of construction. An important parameter in the environmental problem is the consumption of energy and the emissions of CO_2 and other greenhouse gasses which result from the energy requirements.

This research compares insitu and prefab construction methods and determines whether or not there is a difference in emission of CO_2 and energy consumption during the production and construction of concrete viaducts. Furthermore the factors which influence the CO_2 emission and energy consumption in a project are researched. The difference between insitu and prefab construction is not clear cut; therefore it is important to define both construction methods before a comparison can be made.

The research is divided into two parts. The first part is a qualitative analysis of the problem. Information is gathered and analysed to determine the direction of the research, the process of production and construction is described as well. In the second part of the research a tool (the quick scan tool) is developed, to determine the qualitative differences between the two construction methods.

Chapter 1 analyses the problem and defines the research question. The next chapter discusses the set up of the research (chapter 2). A literature study is carried out to gain insight in the problem and determine which factors influence the emissions of a project (chapter 3). Chapter 4 describes the difference between insitu and prefab constructions.

The second part of the research starts with the explanation of the quick scan tool (chapter 5), after that the most important assumptions for the model are discussed (chapter 6). Chapter 7 explains the processes and working of the tool, after that the result of the tool are discussed with the help of a test case. (chapter 8). The sensitivity analysis discusses which factors influence the emissions of a project and thus where research should focus on (chapter 9). A discussion is started about the used calculation values in chapter10. The research is finished with conclusions and recommendations (chapter 11).

PART 1: QUALITAVE ANALYSIS

1. PROBLEM ANALYSIS

1.1. Problem description

The increase in attention to the preservation of the environment there is often focussed on the reduction of CO_2 emissions. These emissions are largely reduced by minimizing energy consumption. Energy reducing measures find their way in all parts of society, from LED lighting to double glazing and environmental friendly cars. The construction industry is also turning its attention to minimize the effects on the environment (Cobouw, 2010). A good example of how the environmental issues are becoming more important in the construction industry is the 'CO_2-prestatieladder' introduced by ProRail (Prorail, 2009). Companies that are taking initiative in reducing CO_2 emissions, receive a virtual discount on their tender. The Dutch government is also investigating the possibility to provide virtual discounts to project proposals which are environmental friendly (Cobouw, 2010). Although the environmental impact of structure is not soley determined by the CO_2 emission and energy consumption, it is one of the most discussed parameters.

The construction industry has, until recently, mainly focused on the residential and non-residential building sector for energy reductions. This is understandable because most of the CO_2 production of buildings is in the user phase (de Vries, 2009). With some changes in the design of a building, such as application of double glazing, the energy consumption can be reduced.

Figure 1.1: Companies are getting increasingly interested in reducing CO_2

The construction industry is now focussing on other sectors to reduce energy consumption and CO_2 emission, like the civil engineering sector. When taking the entire life cycle of the civil engineering sector into consideration, the production of construction materials is responsible for 80% of the energy consumption and the construction process itself for approximately 13%. These are therefore two phases of the civil engineering sector which are interesting for research. Previous studies into the energy consumption and CO_2 emission of the construction industry, have focused on the total amount of energy consumption in the construction industry (Rowings & Walker, 1984), while other studies compared the CO_2 emission of different building materials in the construction industry (Acquaye & Aidan, 2010). Until now, there has been very little research using a project specific approach. When attempting to calculate the CO_2 emission per project, the CO_2 reducing measures are implemented after the design is finished. A good example is the *project carbon calculator* developed by the BAM group (Koninklijke BAM groep NV, 2006). There is no integration of CO_2 reducing measures since they are implemented only after finishing the design. Solutions that are often found are the reuse of materials, the usage of green energy and more efficient ways of transport (like carpooling). Considerations about construction methods or processes are not incorporated in those calculations.

When deciding on a construction method in a project, the deciding factors are mostly: constructability, construction time, location, available resources and financial aspects. The amount of energy used for each construction method and the specific CO_2 emissions, are not factors of great importance in this matter. Given the increasing energy prices and attention from clients to reduce energy consumption, would it be worthwhile to take the energy consumption and CO_2 emission into consideration when choosing a construction method?

1.2. Research focus

The previous paragraph showed that the construction method is not fully incorporated in the design process. Concrete is the most used construction material in the world (Holcim, 2009). The focus of this research combines those two facts. More specifically the research will focus on the difference between insitu and prefab concrete construction, and the question whether or not there is a difference in energy consumption and CO_2 emission between the two construction methods. Closely comparing both methods can provide insight into potential differences in their specific environmental performances. A model will be developed to calculate what the differences are between the two construction methods. This model will also map out the factors that influence the emissions of a project. It is important to realize that a structure is never made 100% prefab or insitu; therefore clear definitions should be set to make distinguish both construction methods.

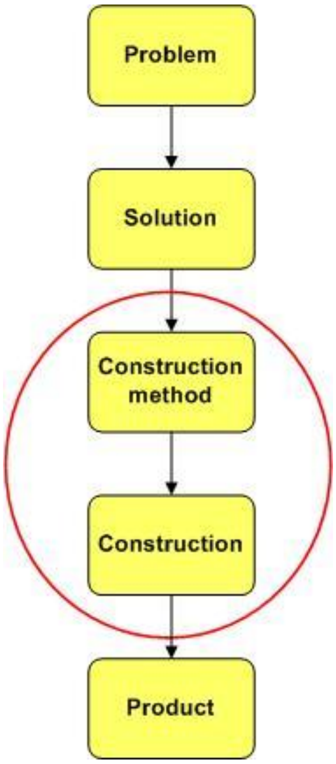


Figure 1.2: Large quantities of concrete are used during construction

1.3. Research case: civil engineering structures

Many construction companies have set themselves goals in reducing CO_2 emissions and energy consumption. Heijmans, for example, is already solely using green energy and is researching options to reduce energy onsite. This research is going to be in cooperation with Heijmans Beton- en Waterbouw and will therefore concentrate on civil engineering. As mentioned before, in this sector about 13% of the total CO_2 emission is emitted on the construction site alone (de Vries, 2009), not to mention the transport and production. In these disciplines the main energy source is diesel, powering the machines and generators used on the construction site. The other large energy source is electricity, which availability and usage largely depends on the location of the building site and the construction methods used in the process. The quantity of energy used and the amount of emitted CO_2 depend on the size of the project, the type of project and the construction method and available resources.

Currently, construction companies design as they have always done, after the design is finished a number of energy reducing solutions are applied for reducing CO_2 emission. In the end this should result in both an energy and CO_2 reduction. The CO_2 emission reducing solutions often result in the use of green energy and more efficient transport (for example carpooling). Construction companies have no integral approach on how to reduce CO_2 emissions during the design process. This research will concentrate on the differences in energy consumption between prefab and insitu concrete structures. After the research it will become clear if the type of construction method has an influence on the quantity of energy consumed and CO_2 emitted. And which factors influence the outcome of the research.

1.4. Problem

It is not clear what the energy consumption and CO_2 emission of different construction methods are in the civil engineering industry.

1.5. Objective

The goal of the research is to explore differences in energy consumption and CO_2 emission, between prefabricated concrete structures and insitu concrete structures during the production and construction of a civil engineering work. The research will yield a recommendation on which factors should be influenced in order to reduce the energy consumption and CO_2 emission and how even more reductions can be obtained.

2. RESEARCH METHODOLOGY

2.1. Research question

Do prefab and insitu built concrete structures differ in their specific energy consumption and CO_2 emission during the production of concrete elements and the construction phase? And what factors influence this outcome?

2.2. Sub questions

The main research question can be divided in to several sub questions. The combination of these answers will result in the answer to the main research question. Below a categorized overview of the relevant sub question is given. It is important to define the terms used in this research, have a clear understanding of the construction process and define a clear scope.

2.2.1. Definition

- What are insitu concrete structures?
- What are prefab concrete structures?
- What are the differences and similarities between CO_2 emission and energy consumption?
- How are the differences between insitu and prefab construction determined?

2.2.2. Process

- What are the main differences in the construction process between prefab and insitu concrete structures with regard to viaducts?
- What is the difference in equipment usage between the two construction methods?
- Which equipment uses energy?
- What is the difference in transport requirements and movements between the two construction processes?
- What is the difference between labour required?

2.2.3. Scope

- Which parts of the life cycle of the construction are going to be incorporated?
- Are side effects going to be incorporated and to what order?
- How are the differences between the two construction processes going to be expressed?

2.3. Scope

A well defined scope is important for the research; it will provide guidance, set boundaries and make the research is conducted in an efficient manner.

The research focuses on the difference between two construction methods; prefab and insitu concrete structures. Therefore, when a comparison is made, it is assumed that both structures have to confirm to the same requirements. The only aspects that will vary are the construction methods. If from study it is concluded that different construction methods require different dimensions, than this will be incorporated. The influence of high strength concrete will be researched, and how this influences the emissions due to transport, onsite and in the factory. Well considered assumptions have to be made on CO_2 emissions and energy consumption in the production process to make the calculations.

The difference in construction method has influence on many factors. The research will focus on the production of (semi-) finished products, transport of construction materials and the construction phase itself. Emission factors will be assumed for other relevant processes. On the construction site, among other things, the number of workers will be influenced as well as the equipment and construction time. Off-site there will be a difference in transportation and production. Also, the equipment which is used is different. The research will start with semi-finished products and end with the delivery of the structure. Only primary energy consumption and emissions will be taken into account during calculation. This includes, for instance, energy consumption on the construction site and transportation. Second order effects like extra CO_2 emissions due to an increase in traffic congestion will not be included.

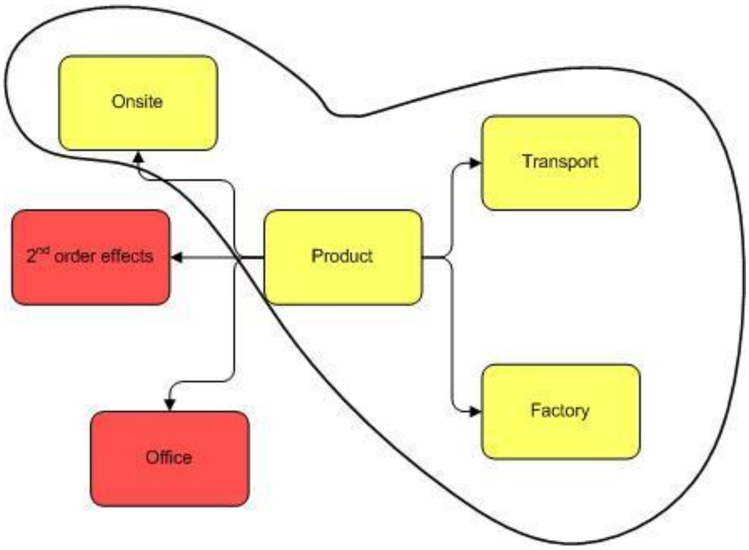


Figure 2.1: Global overview of scope

There are four phases when considering the CO_2 emission of a structure: purchase (of materials), construction, use and demolition. During this research the focus will be on the purchase and construction phase. These phases are important because these can be influenced directly by the contractor. The user phase and the demolition of a civil engineering work will not be incorporated in the scope of the research.

In Appendix A a graphical overview of the total scope is given.

2.4. Research methodology

The research is divided in a number of stages which are discussed in the following paragraph.

2.4.1. First stage: Literature study and interviews

The research will commence with a literature study. This will provide insight into the available information and will highlight where knowledge gaps exist. There are a number of construction methods available when building a structure. It is not the objective of the study to find an exact number for every different construction method, but to get a general impression of the energy consumption and CO_2 emission of that specific construction method. Standard values should be obtained from the literature study. Visits to a number of prefab factories will be scheduled as well as interviews with personnel in the field and planners.

The process will be analyzed using the GHG protocol (World resource institute, World business council for sustainable development, 2002). The focus is on all three scopes. The entire production chain of the construction will be reviewed. In the literature study there is going to be a more elaborate explanation of the GHG protocol.

2.4.2. *Second stage: creating the quick scan tool*

The second stage of the research is the development of a quick scan tool. The quick scan tool will calculate the CO_2 emission and energy consumption of a project. This tool has two main applications. First of all, it helps to answer the research question; which construction method emits less CO_2 and consumes less energy. The tool will give shape to the reasoning acquired by the literature study. Secondly, it gives architects, engineers and contractors insight into the differences of energy consumption and CO_2 emission between construction methods. The first application of the tool is the focus of this research and will therefore be more elaborately reviewed than the second application.

The tool will focus on viaducts. There are a number of reasons to focus the tool on viaducts. The first reason is that a viaduct is the most constructed civil engineering work in the Netherlands; the tool can therefore be used widely. Another reason is that focussing the tool on one type of structure makes it possible to gather specific information about the construction of the structure. This will improve the depth and thus the quality of the outcome of the research. Whether or not these results can be applied on other civil engineering works should be investigated.

A concrete structure is never completely insitu or prefab. The tool will incorporate this by dividing the structure into elements and different types of construction methods. The tool will incorporated among other things, the transport distances, the quantity of concrete used, equipment used and emissions in the (prefab) concrete factory.

2.4.3. *Third stage: Results and sensitivity analysis*

The third stage of the research is the review of the outcome of the tool, utilizing input from a test case. A real viaduct which has already been constructed is used for input. The outcome of the tool will provide the first insights whether or not there are differences between different construction methods, with regard to energy consumption and CO_2 emission. After the first results are available, a sensitivity analysis will be performed in order to determine which factors influence the results of the research. This is crucial for the research, because it will demonstrate which elements of the emissions can be influenced. This will help the construction industry and other actors in reducing CO_2 emissions. The third stage of the research is concluded with a review of the calculated and the assumed values.

2.4.4. *Fourth stage: Conclusions and recommendations*

The research is concluded with an answer to the main research question – which construction method is the most environmental friendly in terms of energy consumption and CO_2 emission; the factors that influence the outcome, will also be incorporated in the conclusion. The combination of these conclusions will result in recommendation on how CO_2 emissions and energy consumption can be reduced during the production and construction of concrete structures. In the conclusions it is important to discuss which conclusions do only apply to the production and construction of viaducts and which are applicable to the entire civil engineering sector.

Figure 2.2 displays a flow diagram of the process of the research.

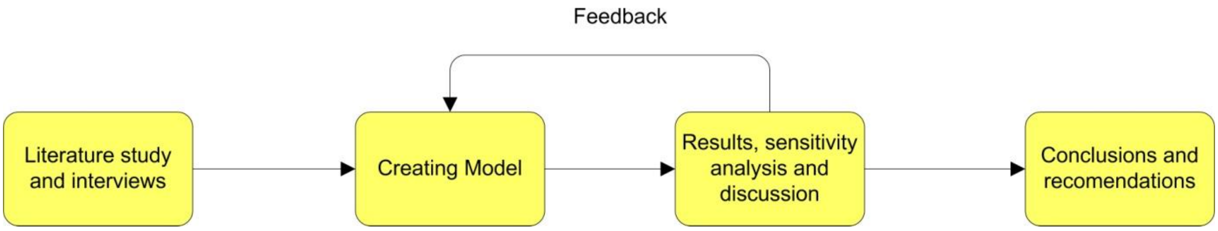


Figure 2.2: Flow diagram

3. LITERATURE STUDY

3.1. Introduction

The literature study will provide information about the general problem and which factors are of influence on the CO_2 emissions. The literature study also provides calculation values and assumptions for the model. In the first paragraph the GHG protocol is explained. The following paragraphs focus on the energy and CO_2 emission in the production and construction process. The influence of cement and reinforcement is discussed, as well as the influence of transport on the construction process. Differences between the various construction methods are also discussed. In most cases only a qualitative description is given, the actual calculation values will be discussed in Appendix P.

3.2. GHG protocol

The most commonly used method of calculating greenhouse gas emission is the *greenhouse gas* (GHG) protocol. This protocol provides a guideline and a calculation method for accounting greenhouse gasses. The greenhouse gasses used in the protocol are the same as covered in the Kyoto protocol. These are CO_2 (Carbon Dioxide), SF_6 (Sulphur Hexafluoride), CH_4 (Methane), N_2O (Nitrous Oxide), HFCs (Hydro fluorocarbons) and PFCs (Per fluorocarbons). The most well-known of those elements is CO_2, because CO_2 is the main GHG that is produced when fossil fuels are combusted. The GHG protocol contains 3 scopes when calculating GHG emissions:

- **Scope 1**: Account for the direct GHG emissions that occur from sources that are owned or controlled by a certain company.
- **Scope 2**: Accounts the GHG emissions that are produced from purchased electricity.
- **Scope 3**: Deals with the consequences of the activities of companies. The activities occur from sources not owned or controlled by the company.

The calculation of scope 3 is not always obligatory. In this research all the scopes are important, because the whole production and construction process is discussed. GHG calculations are based on (well) documented emissions factors and are expressed in CO_2-e (World resource institute, World business council for sustainable development, 2002).

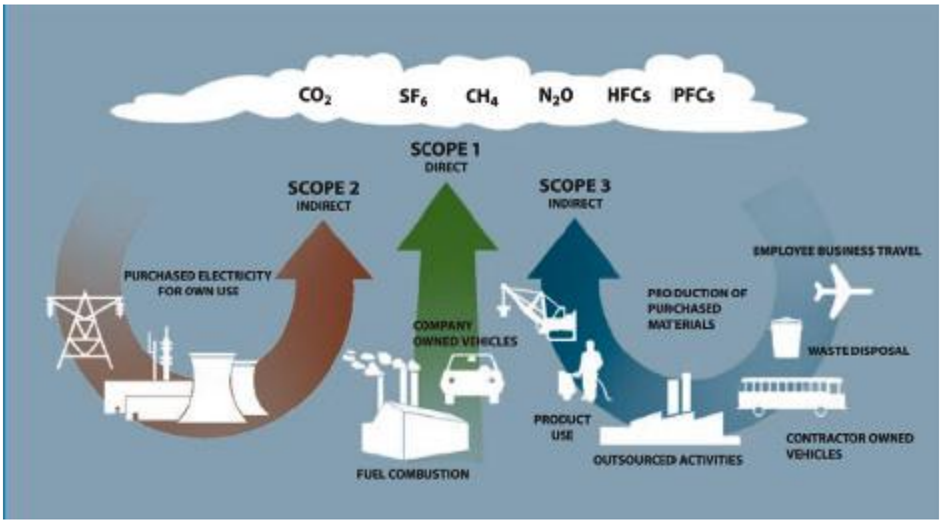


Figure 3.1: Scope 3 analysis of GHG protocol

The distribution of emissions over the 3 different scopes is not the same in all calculation. For example the GHG protocol places airtravel (business) in scope 3, while ProRail places air travel in scope 1.

3.3. Energy and CO_2

Energy consumption and CO_2 emission are closely linked together. The CO_2 emissions of a construction process consist of fuel (diesel) and electricity. When calculating the energy consumption and CO_2 emission of a project it is important to research the electricity and fuel consumption of all the different processes in the production and construction process. Onsite a lot of diesel is used, but also different types of fuels for heating of the site office. More important than the CO_2 emission is the CO_2 equivalent emission (CO_2-e). As stated in the paragraph above CO_2 is not the only GHG, there are others which also contribute to the problem. To make it possible to compare different processes one value needs to be found to make this comparison, this is the CO_2 equivalent (CO_2-e). In Table 3.1 an overview is given of the greenhouse gasses and their CO_2-e value. In literature all emissions are calculated back to CO_2-e, but it is often referred to as CO_2. In the rest of the research, when CO_2 is discussed this comprises all the greenhouse gas potential. ProRail is one of the first companies who have started to let CO_2 emissions be a part in their tenders. In cooperation with SenterNovem, a list of emissions factors is drafted (SenterNovem, December 2009). These emission factors are going to be incorporated in the model as calculation values. It comprises values of emissions factors for transport and electricity. The total overview of emission factors is given in Appendix B.

Greenhouse gas	CO_2-e
CO_2	1
CH_4	21
N_2O	310
SF_6	23900
HFEs	100-500
HFCs	150 – 11700

Table 3.1: Overview of green house gasses and CO_2-e

There are 3 main steps to reduce CO_2 emissions; Step 1: Reduce unnecessary energy consumption. Step 2: All electricity used is green electricity. Step 3: If fossil fuels are required, use them as efficient as possible.

3.4. Fuel and Electricity

The energy required in the entire construction process can be divided in two main categories, (fossil) fuel and electricity. Electricity is required on the construction site and in the factory. Fuel is used in transport and in the equipment onsite, mostly as diesel. With the transport of people petrol is also used. In factories fuel can be a number of things: diesel, gas, but also biogas and garbage. On the construction site the quantity of diesel and electricity used, depends on a couple of factors like the type of project, the size of the project, the availability of electricity and construction method. In Figure 3.2 an overview is given of the CO_2 emissions of Heijmans Infra. It shows that the largest emissions of a construction company come from lease cars, fuel onsite and the tarmac factory. The emissions of scope 3 are only due to transport, the purchase of construction material is not incorporated in this.

Electricity is the other big energy contributors. ProRail has determined the CO_2 production for each producer of energy in the Netherlands. The emission factor of electricity varies from 0,650 kg CO_2/kWh for grey electricity to 0,015 kg CO_2/kWh for green electricity. The variations in values are due to the difference in installations used to generate the electricity and the methods which are applied. In accordance with the GHG protocol, using green electricity reduces CO_2 emission. As can be seen from the emission factors (Appendix B), there is a considerable difference in green electricity and grey electricity. The implementation of green electricity reduces the CO_2 emission but the quantity of energy consumed is not. Construction companies regard green energy as one of the biggest possibilities to reduce CO_2 emissions (like Heijmans). Other ideas are more unorthodox like placing temporary windmills on the construction site (van Hattem en Blankevoort, 2010).

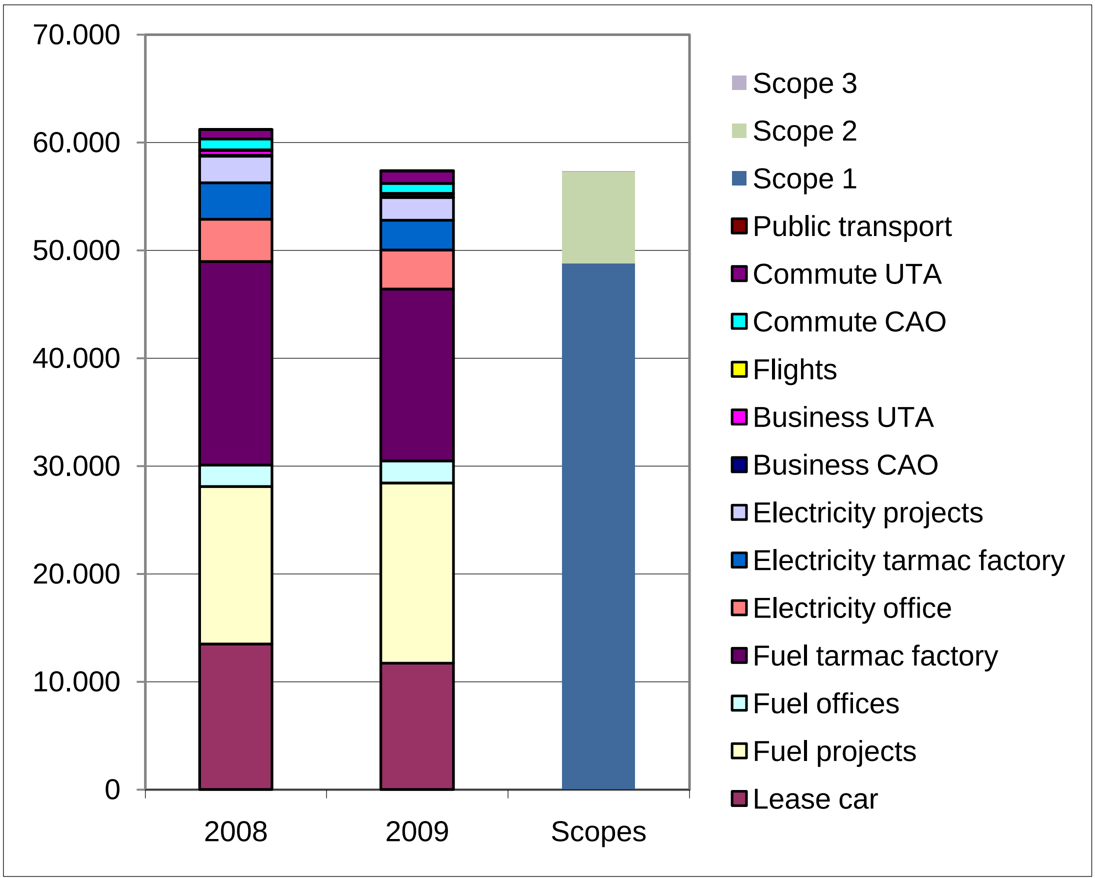


Figure 3.2: Overview of emissions (ton CO_2) of Heijmans Infra and distribution over scopes

3.5. Cement, concrete and reinforcement

3.5.1. Production concrete

Concrete, in the most basic form, is a mixture of cement, sand, aggregates and water. Often admixtures are added to improve or alter characteristics of the concrete. The composition of concrete depends on needs of the user. Needs often concern strength, workability and hardening time but it is also possible to change the colour of concrete. An overview of typical concrete mixtures is given in Appendix F. Typical mixtures are determined to apply in the model. In the rest of the research these emission factors are used, but in reality these can be different from project to project and climate to climate.

Cement

In the production of concrete the biggest contributor to CO_2 emission and energy consumption is the production of cement. The exact quantity of CO_2 emission varies per study, country and type of cement (Appendix C). In Europe it is about 0,75 t CO_2-e /ton (Cement & Beton centrum). Construction materials contribute about 75% of the total CO_2 emission of a construction process (Flower & Sanjayan, 2007). The most common type of cement is Portland cement and contributes of about 5% of the total annual CO_2 production worldwide (Flower & Sanjayan, 2007). Other cement and concrete types are mixtures of Portland cement with different kinds of aggregates like fly-ash and ground granulated blast furnace slag (GGBFS). Both fly-ash and GGBFS are by-products of steel production processes so the materials are already available. Because these materials replace a part of the Portland cement the CO_2 emission is less. In the Netherlands, on average, only 48% of the cement consists of clinker (ENCI). With the substitution of aggregates an enhancement in the properties of concrete can be acquired (Bremmer & Eng, 2001). The CO_2 emissions and energy consumption can differ considerably between countries. For the Dutch cement industry, the typical CO_2 profile of the cement production is as follows (Figure 3.3). The Netherlands is one of the leading countries with regard to the use of alternative fuels and replacing clinker with alternative materials. In Appendix C the production process of cement is given, also an overview is given of the quantity of clinker and usage of alternative fuels in de cement production worldwide. Appendix C provides also an overview of the minimum and maximum level of clinker in cement.

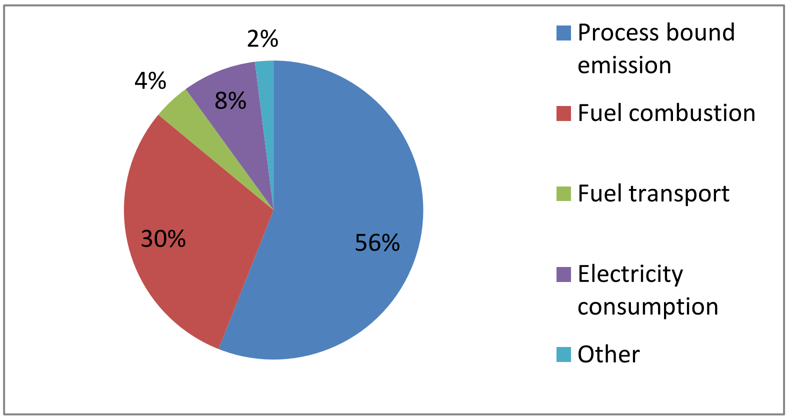


Figure 3.3: CO_2 emission of cement (%) per contributor (Cement & Beton centrum)

A general rule is that to obtain a higher strength concrete, more cement needs to be added. There are five types of cement (CEM I, II, III IV and V), each type of cement has a maximum and minimum of admixtures (like fly-ash) that is allowed to be added. In CEM I almost no admixtures (<5%) are allowed, in CEM III (<90%) a whole lot more admixtures are allowed (Cement & Beton centrum). CEM IV and CEM V are special types of cement that consist of different types of admixtures.

To reduce the energy requirements of cement research has been conducted. Possibilities are found in alternative fuels and improved heat recovery (U.S. Department of Commerce, 1977). From 1975 on there has been an energy reduction of 33% on the production of cement (Shepherd, 2005). Even though big improvements have been made, the process bound emission of cement is unavoidable (see Appendix C).

Concrete

The total quantity of energy required to produce concrete is 1129 MJ/m^3 (Cement&Beton Centrum); this is divided over different contributors, displayed in Figure 3.4. The values extracted from the research from Beton&Cement will be used because it has the Netherlands as reference and is therefore useful for this research.

Each different factory for concrete, cement and reinforcement has a different CO_2 footprint. Each factory uses different processes, electricity and fuels. Therefore exact numbers are hard to define, the assumed values in this research are values found in literature, but can differ from factory to factory.

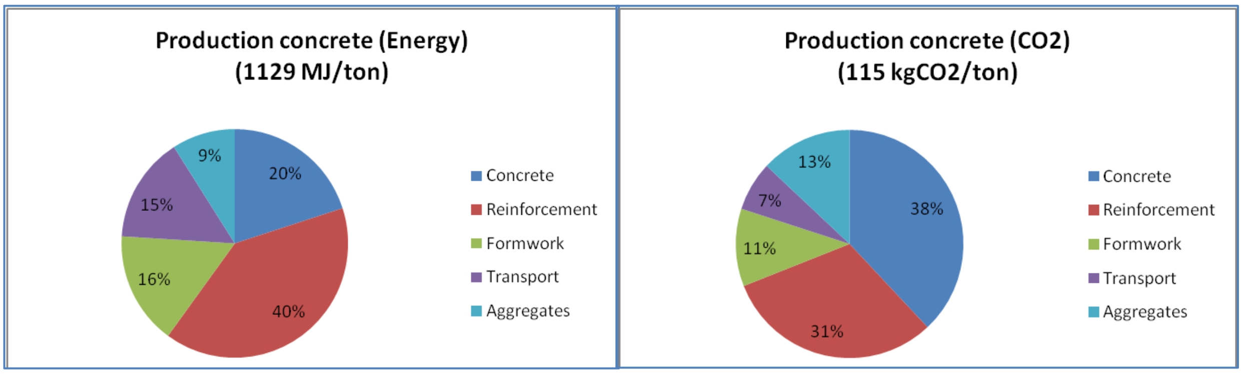


Figure 3.4: Energy consumption and CO_2 emission of concrete (Cement & Beton centrum)

It is clear that the biggest contributors to the CO_2 emission are cement closely followed by reinforcement. From a contractors point-of-view these processes are difficult to influence. When CO_2 reduction must be obtained, optimization is important. For a contractor the easiest factors to influence are transport and formwork (onsite energy use).

Considering the production of concrete there are more factors that influence the energy consumption and CO_2 production than only cement. A lot of energy is put in the winning and production of aggregates, up to 20% (Flower & Sanjayan, 2007). Energy reductions could be found in the reuse of concrete. Because of the environmental impact of concrete, the effectiveness of the usage of concrete will be very important. Because concrete and cement can have so many different compositions, some basic calculation values should be applied. Reinforcement in concrete is also a big contributor to the energy consumption and CO_2 emission. Concrete is, in the construction industry, most common applied as reinforced concrete, the production of steel for the reinforcement is a significant contributor to the CO_2 emission and energy consumption and is estimated about 40% of the total amount of required energy.

The CO_2 emission of a civil engineering structure is for the largest part provided by the production of construction materials (83%) (Figure 3.5). The CO_2 emissions during construction are 13%. When the structure is in use, only 4% of the total CO_2 is emitted. The most used construction material in the civil engineering industry is concrete (Holcim, 2009).

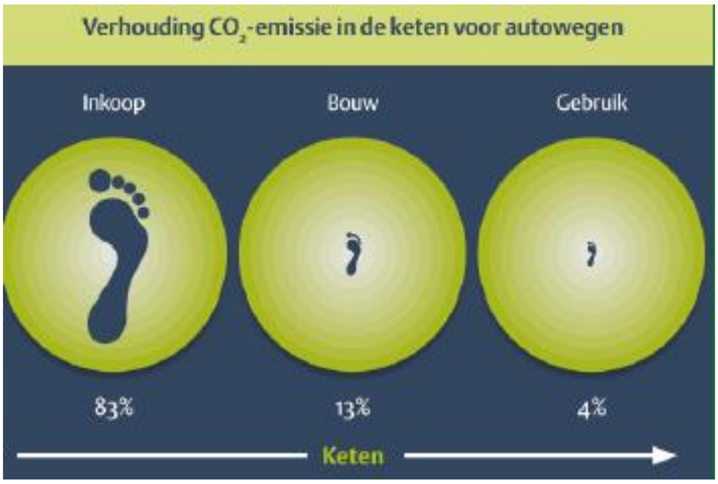


Figure 3.5: CO_2 emission of civil engineering sector (83% Purchase, 13% construction, 4% usage)

Comparison

Comparing concrete to the other two most used building materials, wood and steel, concrete comes in second, with regard to energy consumption and CO_2 emission. Wood is, from an environmental perspective the best construction material, because it is CO_2 neutral. Wood has a number of downsides, like its structural applications and availability. The production of steel requires more energy than concrete. Although steel is much stronger than concrete, when compared to each other concrete is the most energy efficient solution (Figure 3.6)(Kreijger, 1979). Onsite, concrete is the most energy consuming material, but this doesn't weigh up to the quantity of energy which is required to produce steel (Cole, 1998).

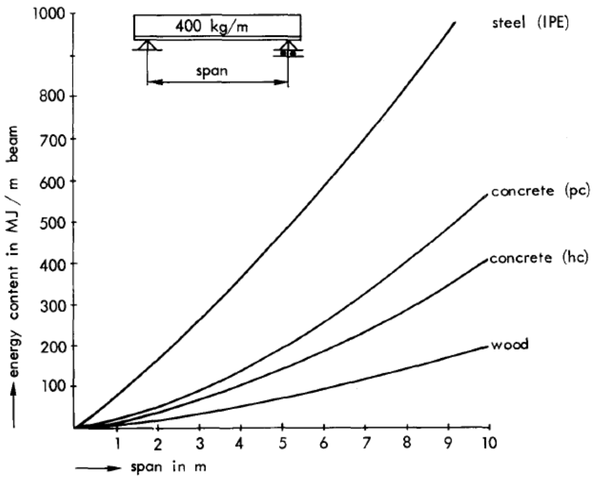


Fig. 3. Energy content (per metre beam) of wood, reinforced concrete and steel as functions of the span, for simply supported beams.

Figure 3.6: Energy consumption per meter material

3.5.2. High strength concrete

High strength concrete is produced by reducing the water-cement factor, improving the mixture with more balanced aggregates and using admixtures like fly-ash and super plasticizers the concrete gets more compressive strength. The most important difference between different strengths of concrete is the type of cement C35/C45 consist of CEM III, C53/C65 consists of CEM I and CEM III, CEM I is Portland cement with no additives, and therefore very high in CO_2 emission. High strength concrete is more easily applied in prefab concrete, but is also used onsite. Nowadays C45/C55 and C53/C65 concrete is standard applied in prefabrication concrete (Appendix D). Concrete with higher strength is not commonly used. Because, in general, there are other limiting factors than the strength of concrete which will determine the size of the element. These limiting factors can be hardening time or transportation loads.

3.5.3. Conclusion

It is impossible to determine exact numbers for the emissions of production of cement and concrete. This has a number of reasons. First of all the concrete mixtures are different for each project. Second of all, the cement and concrete factories work with different production processes therefore the efficiency is different for each factory. Furthermore, each factory uses different fuels to power the process; this will have great reflection on the CO_2 emission of the factories.

The definitive calculations are given in Appendix F and will be discussed in Appendix P.

3.6. Transport

In the Netherlands, the transport of raw materials mainly occurs with inland shipping. Ships can take huge cargo, and are very suitable for the transport of raw material. Another advantage is that ships use less than twice the amount of fuel than a truck does, although it is predicted that the gap between the two transportation means will become smaller (Rijksinstituut voor volksgezondheid en milieu, 1997)(Federal Railroad Administration, 2009).

There are less prefab factories in the Netherlands than concrete factories; therefore the average transport from a prefab factory to a construction site will be longer than with concrete.

There is more equipment required on site when constructing insitu than prefab. Insitu concrete construction requires also more labourers on the construction site for a longer period of time, this requires more personal transport. From the ProRail guidelines the calculation values for transport can be obtained (see Appendix B).

3.6.1. Methods of transportation

There are 3 basic manners of transportation that are going to be discussed in this research. Inland shipping, transport by truck and transport by car. Transport via train is not going to be discussed because transport via train is only beneficial for great distances. The number of products transported via train in the construction sector is also not large.

Transport is not always maximizing their efficiency. Ships are not loaded to their full capacity and trucks return without cargo. It is important to take these considerations into account in the rest of the research. Appendix P discusses the calculation values and emission factors of transport.

3.6.2. Inland shipping

The share of inland transport is significant in the Netherlands. Inland ships can take huge cargo. Depending on the waterway and ship, up to 5500 ton can be transported. A disadvantage of inland shipping is that in most cases after transport is required. This subject is not of interest in this research, because transportation of raw materials is directly to the prefab or concrete factory. Inland shipping can be divided in a number of weight classes:

- 350 ton (Spits)
- 550 ton (Kempenaar)
- 1350 ton (Rhine Herne Canal Ship)
- 5500 ton (Koppelverband).

Most of the concrete and prefab factories are situated alongside waterways. All the primary materials will therefore be transported to the factories by inland shipping. Even though ships do not travel at great speeds the quantities that can be transported in one day outperform any truck. Another advantage is that waterways do not have traffic jams, the delivery of material can therefore be planned very precisely. Because concrete and prefab factories plan their production long way ahead the fact that ships do not travel that fast is not a big issue. Transport by ships is more efficient than by trucks.

From 2010, inland ships will use diesel as fuel instead of oil fuel (CE Delft, 2008). This will reduce the emission of inland ships.

3.6.3. Transport by trucks

The transport of the construction materials to the construction site is done by trucks. There is a divide between two types of trucks, bulk and non bulk. For transport to a construction site most of the transport is bulk. If prefab elements exceed maximum dimensions, special permission and transport is required to transport these elements.

3.6.4. Other transport

Besides transportation by truck there are other transports that are worth mentioning. Different types of transport are; concrete pre mixers, concrete pumps and pile driving equipment.

3.6.5. Transport by cars

The whole work force needs to commute to the construction site. It is assumed that everyone comes by car. Construction sites in the civil engineering sector are often hard to reach. Because workers start early and construction sites are hard to reach, public transport is not an option. In the construction industry it is promoted to carpool with colleagues.

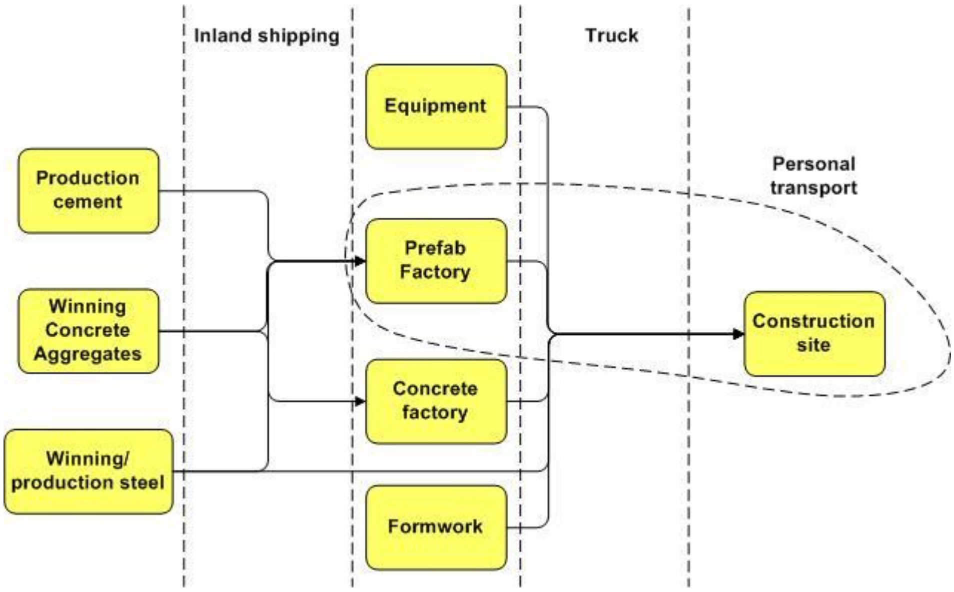


Figure 3.7: Overview of transport flow and transportation means which are taken into account

3.7. Construction method

3.7.1. Insitu

The definition of insitu is: "In the place" (van Dale). This seems like a very straight forward definition but it is actually subjective. Everyone has a different definition of insitu construction, it is important when designing the tool that the definition is clear, this will be discussed in chapter 4.

Each concrete product, whether it is insitu, prefab or a mixture of both methods, has its own characteristics. In general it can be concluded that an insitu product has more transport of equipment, more equipment use on site and more labourers (Cole, 1998).

Improvements in the CO_2 emission and energy consumption of insitu concrete structures could be obtained by reducing strength overkill of the construction. Better optimized structural elements and later loading of the structure will give the structure time to gain strength and therefore reduce the quantity of concrete used. This will reduce the quantity of CO_2 emitted (van Hattem en Blankevoort, 2010).

3.7.2. Prefab

Prefab has a number of known advantages, like reduce building time and minimizes traffic hindrance. The question arises if it can also reduce energy consumption. Prefabrication is defined as: (concrete) elements produced on another place than the construction site to be assembled on site (van Dale). This definition leaves room for discussion. Where is the element produced and how is it produced? In chapter 4, there will be more elaboration on this subject. There are considerable differences between different types of prefab production processes, in time and energy consumption (Bennenk, Kuik, & Wapperom, Prefab Beton Deel1, 2003) (Bennenk, Kuik, & Wapperom, Prefab beton deel 2, 2003). The choice of type of mould depends on the quality required and the number of concrete elements that are produced from that mould.

Quantity of construction material

The quantity of concrete used in prefab elements can be greatly reduced in comparison with insitu concrete. This has a number of reasons. 1) Precast elements have often the same dimension, therefore the quantity of concrete and reinforcement can be optimized. 2) Prefab elements are lighter because prefab elements are produced with high strength concrete. This results in material saving (Yee, 2007).Another difference between insitu and prefab concrete structures is the quantity of waste reused. In a prefab factory there is no residual concrete and there are no concrete trucks sent back to the factory. Prefab factories have a closed chain of materials; this means that they do not produce waste (see Appendix D). Even though waste and the use of materials is not part of the scope of this research, it is a factor that cannot be forgotten.

Improvements in the prefab process

Quantities of concrete and reinforcement are the biggest contributor to CO_2 emissions of a concrete structure. Important is the role of quantity and type of cement used in the concrete mixture. Because prefab elements are produced industrially, a focus is on fast production. Prefab concrete elements will therefore, in general, consist of more cement, because this increases the initial strength. Although there should be noted that prefab factories also see the environment as an important item on the agenda and have started a number of initiatives to reduce the quantity of cement in concrete. For example, prefab factories have extended their production cycle time on some products (Appendix D). This increase in cycle time gives the products a longer time to harden; therefore less cement in concrete is required. Another innovation is the heating of the elements, this speeds up the hardening process and results in a reduction of cement. Because prefab elements are produced industrially the strength of the structural element can be determined more precise and the structural element can be more easily optimized.

In Appendix E an overview is given of the pros and cons of insitu and prefab constructions.

3.8. Conclusions form literature

From the paragraphs above some important conclusions can be drawn up. First of all it becomes clear that the energy used in the production of concrete is considerable. Although this research is, on various reasons, not focused on the production of concrete it is important to acknowledge that using the material in the most optimal way is important. Comparing the construction of prefab and concrete structures, both have their advantages and disadvantages. Insitu needs more workers and equipment this very energy consuming. The concrete is also used less efficient. An advantage of insitu is that transport is in general more direct and formwork is kept longer in place which gives the concrete more time to gain strength. Judging prefab on its pros and cons it is clear that one of the biggest advantages seems to be that less equipment is required on the construction site, also the energy consumption on the building site is lower. Prefab elements can be produced lighter with higher strength concrete. The down side of prefab is that the factory will use more energy and prefab concrete will in general contain cement which emits more CO_2.

4. INSITU AND PREFAB CONSTRUCTION METHODS

4.1. Introduction

This chapter discusses the differences between insitu and prefab construction methods. The definition of both construction methods is given as well as different types of insitu and prefab construction. The influence different construction methods have on the usage of equipment and quantity of labour is discussed as well.

4.2. Insitu

4.2.1. Introduction

Insitu concrete construction is the oldest way of constructing with concrete. Nowadays the process is improved but the idea stays the same. In the next paragraphs, first the definition of insitu construction method is explained. After that the prefab construction method is discussed.

4.2.2. Definition

As mentioned before there is no clear cut difference between insitu concrete construction and prefab concrete construction. Most insitu concrete structures consist of some prefabrication. Because the definition of insitu concrete is not clear enough, a definition in this research needs to be formulated.

In this research, the definition of insitu concrete will be: Each concrete element or structure which is poured onsite and is not moved afterwards. If a (whole) structure is insitu it therefore means that all the concrete is poured onsite, on his final place. Reinforcement is not included in this definition; this can also be prefabricated in a factory. It is outside the focus of this research to include this.

Insitu concrete construction applies prefabricated elements to improve the speed and quality of the structure. These elements can be, for example, formwork, reinforcement or a floor which needs a finishing layer. Therefore a moving scale should be defined, which discusses the amount of prefabrication in the process. To settle this problem, there will be a partition between different construction methods in different categories. Only construction methods will be discussed, prefabrication of reinforcement will not be discussed.

4.2.3. Different types of insitu concrete constructions

Appendix G shows there are different types of formwork. The usage of different types of formwork influences the quantity of energy and the number of man-hour required for the project, therefore it influences the quantity of CO_2 emitted. In this research there is going to be a divide between three types of insitu concrete.

- Insitu with traditional formwork
- Insitu with standard formwork
- Prefabrication onsite

Figure 4.1: Formwork and falsework for deck construction

Insitu with traditional formwork

Element or structure constructed with formwork made for a specific project. All the formwork is used once and is produced onsite. Constructing in this manner is very labour intensive. The usage of material is not always optimal, and there is no benefit in repetition.

Insitu with standard formwork

Standard formwork is more efficient than traditional formwork. Standard formwork has standard sizes and is designed to be assembled with great speed due to standard connections. There are a couple of companies (like PERI) who deliver the formwork and calculate which falsework is required for the construction. There are a number of advantages over the traditional formwork. First of all, complete formworks can be reused and this saves time. After the project the formwork is dismantled in standard objects and can be reused on different projects. There is therefore little waste in formwork. Even though this type of formwork consists of standard elements there is almost no limit to the different kinds of shapes that can be produced. The second advantage is that the connections are standard; people who are familiar with the system can therefore construct formwork in high speed. Another advantage is that the companies, who rent out these types of formwork, have experience with the formwork. They can give information about the strength and capabilities of the formwork. Because the formwork is reused a number of times, the impact of the environment is less than with traditional formwork. Although this will not be incorporated in the tool, it is something to keep in mind.

Prefabrication onsite

Prefabrication onsite is defined in this research as elements produced on the construction site, but on a different location than its final place. This is done when there are special demands to the structure that needs to be built. A drawback is that it uses the bad sides of both insitu construction and prefabrication construction. The arguments to construct this way are mostly because an element is too big to transport over the road and it is not possible or desirable to construct it on his final place. A typical reason to construct in this manner is with a new bridge or viaduct for a (rail)road, when closing of a road is not desirable.

4.2.4. Labour

The amount of labour that is required, onsite, to construct an insitu concrete structure is, in comparison with prefab, large. The process consists of:

- Constructing formwork
- Placing reinforcement (sometimes pretension)
- Pour the concrete
- Compact the concrete

The transport of these people is a contributing factor to the CO_2 emissions. Due to the great amount of actions onsite the construction time of an insitu structure is longer than with prefab. The distance the labourers need to travel to the construction site will, in general, be larger than the distance to a prefab factory. People tend to move near to their work, when working on a construction site, this varies from time to time. Therefore travel distance will in general be longer than travel to the prefab factory.

Considering the quantity of CO_2 emitted during the transport. The biggest contributor isn't the transport of the material, but more the transport of equipment and people (Cole, 1998).

4.2.5. Equipment

The usage of equipment during the construction of an insitu concrete structure is considerable. The transportation and installation of formwork, cranes and falsework is required to start the construction. There are a lot of specialized labourers required for each task in the process; each will need to have their own tools.

The typical energy consumers on the construction site are: Cranes, generators, prestressing equipment, concrete pumps, compacting equipment foundation ram and the site office.

4.3. Prefab

4.3.1. Introduction

The Netherlands is well-known for its application of prefab elements in constructions. This has a number of reasons: 1) In the Netherlands space is very limited, and therefore construction sites are very confined. Constructing with prefab, just-in-time delivery is possible, this will keep the construction site small. 2) Construction time; with the delivery of prefab elements the construction time (onsite) can be reduced. 3) Quality, producing elements in a controlled environment makes sure the quality of an element is as good as possible; elements can be checked before leaving the factory. 4) Labour in the Netherlands is very expensive. Constructing with prefab is almost always faster which reduces labour costs.

The next couple of paragraphs explain the definition of prefab in this research, which types of prefab are available and what the influence are on the equipment and labour.

4.3.2. Definition

Prefab concrete structures are defined as structures which consist of elements produced in another place than the construction site. In this research a prefab structure is considered a structure which consists of one or more elements produced in another place than the construction site.

This research focuses only on prefabricated concrete elements. Prefabrication of formwork and reinforcement is not considered as prefabrication in this research.

4.3.3. Different kinds of prefabrication

In Appendix H an overview is given of a number of prefabrication processes. This research will consider two different types of prefabrication; Project specific prefabrication and "off the shelf" prefabrication.

Project specific prefabrication

The first method of prefabrication is the production of unique elements specific for one project. When the architect has specific demands about the shape of a structural elements or because only a few repetitions are required this type of prefabrication is considered. Making formwork in a factory is easier than onsite because all the tools are available and there is a supply of material. Pouring the concrete in a controlled environment ensures the quality of the concrete elements. A downside is that there are little advantages of large scale production, because formwork is made for a specific project. The process can be compared to production of insitu elements onsite.

"Off the shelf" prefabrication

Prefabrication "off the shelf" are prefab elements which are made in a highly automated fashion. The formwork is fixed and all the dimensions are the same. This type of prefabrication is very efficient. Although all the elements that are produced are still engineered for each project individually there is a large amount of standardization. Formwork is reused many times and is of high quality. The possible material reduction in comparison to insitu concrete elements is also considerable. The formwork is engineered to have the optimal shape; this minimizes material use for both concrete and reinforcement. Producing prefab elements allows for the use of high strength concrete. Standard concrete in a prefab factory is C53/C65, onsite this is not easily applied because of the hardening time of high strength concrete.

4.3.4. Labour

"Off the shelf" prefab concrete elements are produced require (relatively) little labour. Only a handful of people are required to produce a great number of concrete elements. This is different with project specific prefab elements. All the formwork need to be produced for a single project, this requires more labour and time. A lot of work is outsourced by prefabrication companies; this varies from reinforcement to formwork and the production of concrete. In this research it is assumed that reinforcement, formwork and concrete are produced in the prefab factory. On the construction site there are not many people required to install the prefabricated concrete elements.

Figure 4.2: Placing prefab beams

4.3.5. Equipment

The most important prefab equipment onsite is a crane, which is required to install the prefab concrete elements in place. Besides a crane, not much equipment required to place the concrete elements. The energy required in the factory is larger than with insitu concrete structures. The machines need to be operated for example and energy is required to regulate the climate in the factory. The transport of elements is also different than from insitu. As can be concluded from the literature study there is more road transport required to transport prefab elements than wet concrete, but less transport is required for the transportation of equipment and labourers.

It is important to acknowledge, that with prefab concrete structures there is a limit to the size of the elements that can be produced. These restrictions can come from the factory or transportation company. Over the road the maximum weight of an element that can relatively easy be transported is 30 ton. When elements get heavier, or exceed the maximum size transportable on a truck (18,75m and 50 ton), special permission is required. If the construction site allows it, it is also possible to transport much larger elements by ship. This is especially popular with tunnel elements or elements for a bridge.

4.3.6. Calculation values

Yee shows that large reductions in material usage are possible when using prefab and/or prestressed concrete (Yee, 2007). Considering the reductions possible in the floors, reductions of about 45% concrete and 45% reinforcement can be achieved (Appendix I).

There are also reductions in other fields, from Cole it can be obtained that especially the transport of equipment and people can be reduced when constructing in prefab (Cole, 1998). Although in the model different (more specific) numbers will be used to calculate the structure than used in Appendix I, Appendix I provides a good image about the material reducing potential of prefab.

4.4. Conclusion

The construction of insitu concrete structure requires more equipment and man-hours. This influences the emissions of the construction process. To determine calculation values is difficult because each structure has its own characteristics. Basic calculation values are obtained from interviews with calculators and literature study on energy consumption of equipment. In Appendix P an overview is given of the calculation numbers used in the model.

With the production of prefab elements reduction of construction material can be obtained. This has a positive influence on the energy consumption and CO_2 emission of the structure and the amount of transportation required. The prefab construction process requires less equipment and labourers onsite. As mentioned in the literature study, the distance between the prefab factory and construction site, is in general, larger. The sizes of the elements produced in a factory are restricted by the capacity of the means of transport, and the size of the prefab factory.

5 different construction methods are discussed in this research. Figure 4.3 shows an overview of the different construction method and their origin.

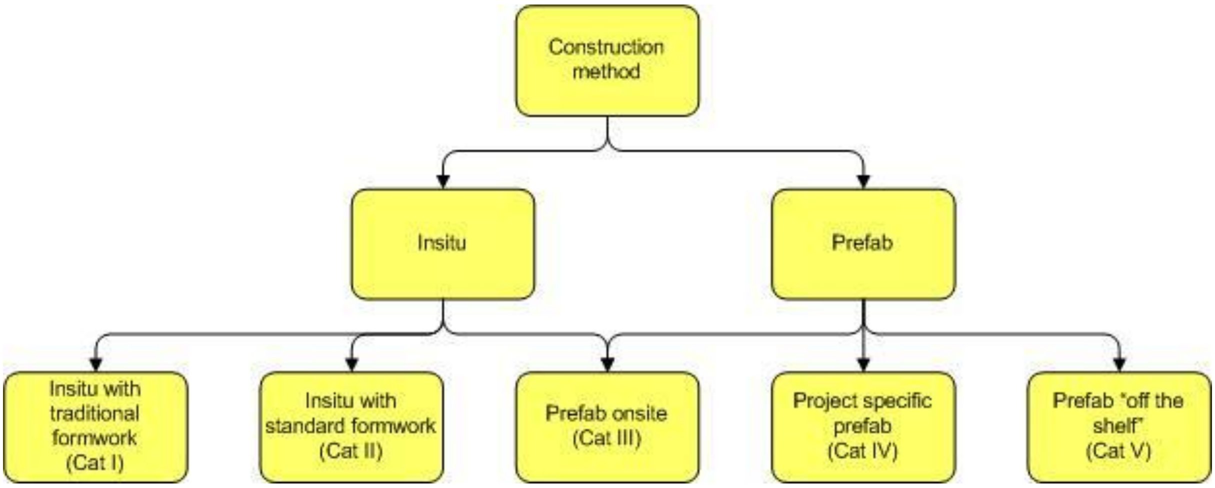


Figure 4.3: Overview of different construction methods

PART 2: THE QUICK SCAN TOOL

5. THE QUICK SCAN TOOL

5.1. Introduction

Developing a quick scan tool will achieve two goals, the research question can be answered and in the future the tool can function as help in the preliminary design of a viaduct. The primary goal of the development of the tool is to determine if there is a difference between the two construction methods, and which factors are of influence on that conclusion.

This chapter will explain the application of the tool, discusses which construction methods are incorporated in the tool. A worst-case scenario is set up to function as a comparison to other construction methods. Furthermore the basic functions of the tool are discussed.

After this chapter the assumptions used in the quick scan tool are discussed. Chapter 7 displays the result of the tool, with the help of a test case. Next a sensitivity analysis determines which factors influence the outcome of the tool, and therefore the emissions during the construction of a project. In the discussion the used calculation values and emissions values are discussed. After these chapters the final conclusion and recommendation is written.

5.2. Application of the tool

In this research the main focus is to determine which construction method, in general, emits less CO_2 and uses less energy. The quick scan tool (QST) will be the mean to determine which construction method is the most environmental friendly. A second function of the tool is to determine the difference in CO_2 emission and energy consumption on a project specific level. This can be in the tender phase of a project, for construction companies, engineering firms or architect bureaus. The QST provides a design team with a tool to give value to considerations made in a project.

Viaduct

The tool will be focused on the construction of a viaduct. This has a number of reasons. First of all will the focus improves the quality of the results. Each different type of civil engineering work has different construction methods. Second of all, this is the first time a tool is designed from this perspective. It is therefore useful to focus the tool for one application; this will make sure the output of the tool is as accurate as possible. In the sensitivity analysis and the conclusions, the focus will shift to more general conclusions. The reason that viaducts are chosen to focus the tool on is because it is the most common civil engineering work. This gives the tool a wide basis. A viaduct consists of a number of elements, which are used in different types of civil engineering works, for example columns, foundation and beams. The results from the tool can therefore be put in a wider perspective. The tool is designed for (single) spans between 15 and 30m. Within this span solid flat slabs are still economical viable. This doesn't mean that the total length of the structure cannot exceed 30m, when columns are used, longer viaducts can be constructed. When spans increase different types of formwork are applied. A deck in prefab (Cat V) is will be constructed with box beams. This has two reasons; 1) box beams are available from spans of 15m to 50m (If spans get shorted the choice is usually made to use (prefab) solid decks) (fib, Task Group 6.4, 2004) 2) box beam have a significant component of weight reduction. Using beams and joining them with a structural topping creates a lighter structure, an advantage of constructing with prefab. Box beams are one of the most commonly used beams in the construction of prefab viaducts. Beams have a high amount of prefabrication only very little work is needed in the factory and onsite, the viaduct is almost directly ready for use. The tool only takes load bearing elements into account.

5.3. Types of construction methods

This research makes a distinction between 5 different construction methods. These categories are already discussed in chapter 4 and are:

- Insitu with project specific formwork (Cat I)
- Insitu with standard formwork (Cat II)
- Prefabrication onsite (Cat III)
- Project specific prefab (Cat IV)
- Off the shelf prefab (Cat V)

Because insitu and prefab elements can be used together in the same project, it will be possible to determine for, each element individually, which construction method has the preference. The elements which are distinguished in a viaduct are:

- Deck/beam
- Columns
- Abutments
- Foundation.

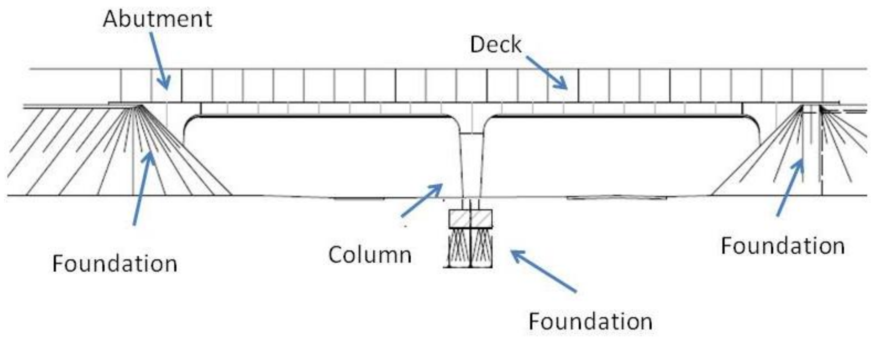


Figure 5.1: A typical viaduct, consisting of a deck, centre columns, abutments and foundation

Deck and beam are discussed as one element. Constructing a deck insitu, the deck will be made in one piece. In prefab construction (Cat V) first beams will be placed and the deck is finished with a structural topping.

The divide between deck/beam, centre column, abutment, foundation is made for a number of reasons. By separating the elements there is an option created to change the construction method per element. This gives the design team the freedom to create the best possible solution and to play with multiple solutions. Two variants can be compared at the same time therefore it is possible to check the differences in emission of two variants. The second reason the separation is made is to make the calculations more exact and easier to check the values. For the production of a column there are different requirements than the production of a deck. This difference can be found in the quantity of reinforcement, prestressing and formwork also the number of man-hours is different. The foundation is build up from two parts; the foundation slab and the foundation piles. Besides the 4 elements there are standard emissions, these are put on a special heading.

5.4. Worst-case scenario

A worst-case scenario is set as reverence for all the other construction processes. This scenario contains the same structure as insitu (Cat I), but with the least environmental energy suppliers in the factory, generators onsite are required for the electricity supply. All equipment is kept the same. Because the electricity requirements are not incorporated in the calculation of the required material, these figure, as well as the figures of transportation are the same. The worst-case scenario is a set up as a comparison to other construction methods, but no premature conclusions need to be drawn up from that name.

5.5. Setup quick scan tool

The quick scan tool is setup to determine the differences between different construction processes. Adjusting the construction method and project variables, the optimum solution can be found. Comparisons are possible, because 2 methods can be distinguished at the same time. This research will focus on a test case, but the tool can also be used to investigate the difference in emissions in different cases. Project parameters are easy to fill in. The output can then be used in the considerations in making the definitive design. The result of the tool shows the difference in energy and CO_2 of multiple combinations of construction methods. Chapter 7 explains the working of the tool works and which sheets contain what piece of information. Appendix P discusses the calculation values of the tool. Appendix R shows screenshots of the model.

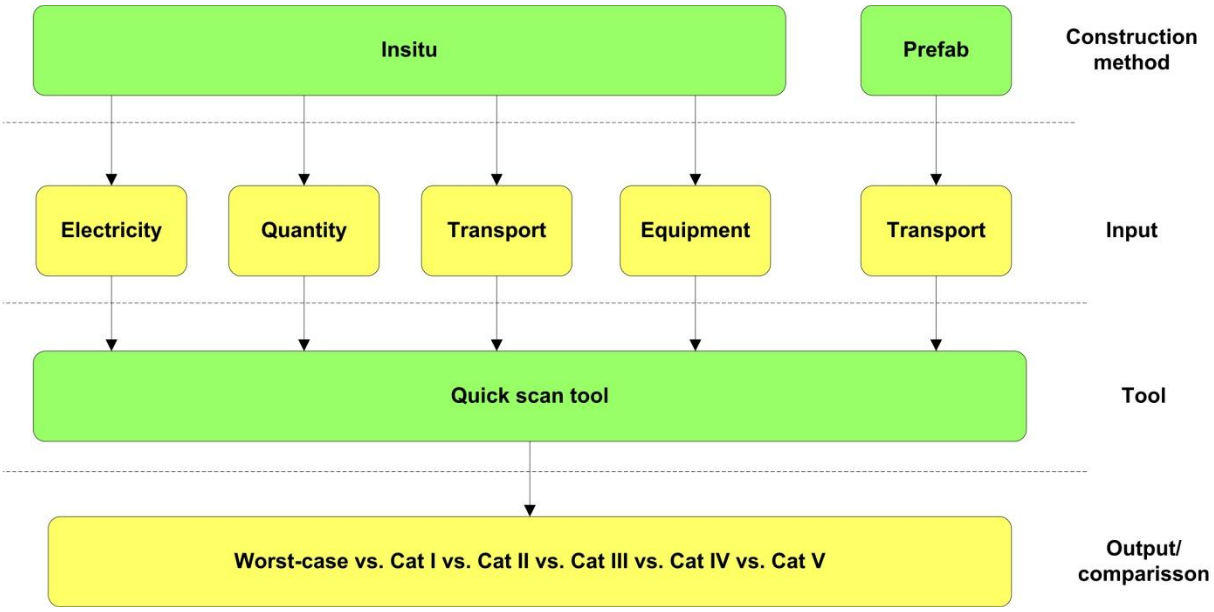


Figure 5.2: Overview of process QST

Figure 5.2 displays the process within the QST. The input of the tool consist of four parts; quantities, electricity, transport and equipment.

- **Quantities**: The quantities and measures of the viaduct need to be filled in. These quantities and measures are of a viaduct constructed insitu.
- **Electricity**: The electricity companies must be filled in used by the construction company, concrete factory and prefab company.
- **Transport**: Transport distances need to be filled in; distances are required from and to concrete factories and prefab factories. The type of car which is used need also be filled in.
- **Equipment**: Type of cranes used onsite (electrical or diesel).

The tool calculates the emissions for all construction methods. The outcome of the tool is an estimate of the emissions of a project. Because a number of assumptions will be made, the emissions of the tool will only be clear on which construction method is preferred; the exact numbers need to be reviewed with certain discretion. The tool is designed to function like a mean to generate insight in the emissions of construction methods, and not as a goal on itself.

5.6. Conclusion

The quick scan tool is a tool designed to determine what the difference in emissions and energy consumption is between prefab and insitu construction methods. Basic project parameters are required to fill in the QST and make a comparison. Assumptions are made to set the basis of the tool.

6. ASSUMPTIONS USED IN THE QUICK SCAN TOOL

6.1. Introduction

A model is a schematic representation of a system. Assumptions need to be made to function as a starting point for the construction of the tool. The following paragraphs discuss the assumptions made in the tool. For every assumption a small elaboration is give why this assumption is made.

6.2. Overview of assumptions

The assumptions are divided in a couple of categories: Model assumptions, structural assumptions and site assumptions.

6.2.1. Model assumptions

- *Raw materials are transported to the factory by ship, and by truck to the construction site.*
  Almost all concrete and prefab factories in the Netherlands are situated beside a waterway. Transporting materials over the water is energy efficient and very convenient because large quantities are easily shipped. It is often not possible to transport the construction materials by water to the construction site; therefore transportation by trucks is required.

- *The production of concrete requires the same energy in a concrete factory as in a prefab factory.*
  The production of concrete is a very simple process. Concrete is a mixture of cement, gravel, sand, water and, in some cases, additives. All these ingredients need to be put in a giant mixer and be mixed until the right consistency. Because the process is simple there are no considerable differences expected. The efficiency can therefore be assumed the same.

- *The quantity of cement in concrete depends on the mixture not on the construction method.*
  First of all, there is a minimum quantity of cement in concrete defined by Dutch regulation (this quantity depends on the type of mixture and environmental class) and is around 300 kg/m^3. Neither prefab nor insitu concrete mixtures can go below that limit. Common knowledge says that concrete mixtures for prefab elements will consist of more cement. Prefab factories are very busy with decreasing the quantity of cement in concrete. Interviews with prefab producers show that the cycle time of prefab concrete elements have been extended to give the elements more time to harden (Appendix D, Appendix M). The concrete moulds are heated up to speed up the hardening. Both interview employees of prefab factories want more freedom in the Dutch regulations, and want to be given the possibility to show what is possible if they are not bounded to these minimum standards. So, even though common knowledge says that the quantity of cement in prefab concrete is higher, there is clear evidence that prefab factories have means to their disposal to reduce this.

- *Cat I has no benefits of repetition, Cat II, Cat III, Cat IV and Cat V do.*
  Production of formwork in Cat I has no advantage of repetition in the formwork because every piece of formwork is unique. Other categories benefit from reusing formwork. Cat II, Cat III and Cat IV construct project specific formwork, but reuse them if more elements are needed on the same site. Cat V uses formwork that can be applied multiple projects.

- *In Cat V there is no man-hour required to construct the formwork, only for cleaning.*
  Constructing a civil engineering work with elements “off the shelf” means there are standard measures that are coming from the factory. The formwork is already available when an element is ordered. Therefore it only needs to be cleaned. Slight adjustments to the element, which are common, are not incorporated.

- *The production of formwork cost no energy.*
  There are a number of ways to produce formwork. Most of the times, formwork is constructed from timber or steel. Steel formwork can be reused a lot of times timber formwork only a couple of times. Timber formwork has less of an impact on the environment than steel (Kreijger, 1979). There are many factors which need to be incorporated to get a clear impression. To incorporate all these factors will not improve the tool too much because the contribution to the total quantity of energy consumption and CO_2 emission is marginal.

- *Waste is of no influence on the score.*
  This research only focuses on the quantity of energy required in the production and construction of a viaduct. The quantity of waste is difficult to determine, there is a lot of waste produced in the factories and on the construction site, but a lot of waste is also reused. Fact is that prefabrication produces a lot less waste than insitu constructions. Because prefab factories have a closed chain of materials, they produce (almost) no waste. With the construction of insitu concrete structures, concrete mixers are often sent back because of delay in the process or too much concrete has been ordered. Although this is outside of the scope of the research, it is something to keep in mind.

- *Carpooling can be used to the construction site, to the (prefab) factory not.*
  In the construction industry it is common to carpool, because workers often have to travel a long way to the construction site. Factory workers often have their own means to come to the factory. It is assumed that all the transportation of people is by car; because factories, but especially construction sites are often located on places, not well reached by public transport.

6.2.2. Structural assumptions

- *Insitu concrete is C35/C45, prefab concrete is C53/C65*
  Onsite it is difficult to use high strength concrete because it is less workable than normal concrete. Therefore the most concrete used onsite is C35/C45. Higher strengths of concrete can be used, but special measures need to be taken. This is the standard concrete mixture which Heijmans uses. With the production of prefab elements workability is not a problem, therefore higher strength concrete is used. The standard concrete mixture in prefab factories is C53/C65; higher strength concrete is not often used. Because the final strength of concrete is often not the limiting factor of prefab elements

- *The deck of a viaduct (except Cat V) is solid*
  Labour in the Netherlands is expensive; reducing man-hours is therefore a must in the construction industry. The fastest way to construct an insitu deck is with a solid deck; this uses the least number of working hours and is therefore cheap. Because solid decks are relatively heavy this means a viaduct will not span more than about 30m. If spans increase the own weight of the structure will increase exponentially. Spans above 30m use different types of formwork, which include weight savings. Prefab beams which span such distances always have weight saving in them (Figure 6.1). Because the formwork only has to be made once reductions in concrete saves money for the prefab producer and reduces reinforcement and weight.

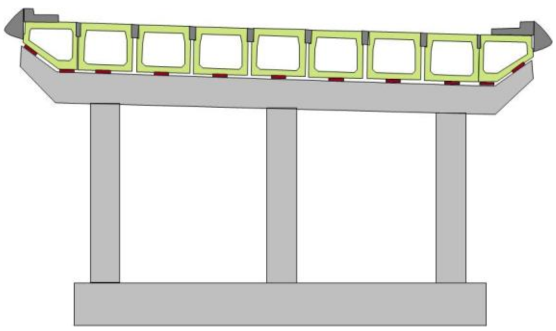


Figure 6.1:Section of prefab deck (with beam)

- *Cat I, Cat II, Cat III Cat IV have no beam in construction Cat V has beams in the construction*
  There are two ways in constructing the horizontal span of a viaduct. When constructing insitu, a deck is poured with reinforcement and prestressing in it. This way of construction is customary in Cat I, Cat II, Cat III and Cat IV (in Cat IV the deck is divided in smaller parts). When constructing with prefab 'off the shelf' it is common to use prefab beams and finish with a structural topping. It is not logical to construct either prefab or insitu structures in another way.

- *All the concrete is reinforced*
  All concrete used in the model is reinforced concrete. No unreinforced concrete is used.

- *All decks/beams are prestressed*
  Concrete has a natural weakness when it comes to tension. When prestressing elements this weakness is (largely) overcome. Prestressing nowadays is common practice in the construction industry; this is incorporated in the model. If prestressing is not used, decks and beams with large spans are not possible.

- *Cat V deck/beam is constructed with a box beam*
  In the construction of decks in category V, box beams are used. Box beams show the full potential of constructing with prefab. There are 3 ways of constructing with prefab; Solid slabs (<15m), inverted T-beam (15m-45m) and box-beams (15m-50m). The overview shows that the range of the box beam fits well with the span of the insitu decks. The characteristics of the box beam can be found in Appendix J. A box beam does not need much finishing when the beams are placed. The application of box beams is one of the most common ways to construct a viaduct.

- *A concrete deck is the same height as a prefab beam*
  The height of a solid flat bed is about 1/30 the length of the span (see Appendix K). From the characteristics of the box beam in Appendix J and Precast concrete bridges (fib, Task Group 6.4, 2004), it can be derived that the average height to span ratio also 1/30 is; therefore it fair to assume that the heights of both deck and beam are the same.

- *In columns, abutments and foundation the compressive force is leading, in the deck the moment.*
  The main force on columns, abutments and foundation is the compressive force. On a deck the bending moment is leading.

- *The same quantity of reinforcement is used in prefab as in insitu*
  For columns, abutments and foundations the most important force is the compressive force. Because concrete is capable of taken compressive force, only a basic quantity of reinforcement is required (125 kg/m^3).

  The quantity of reinforcement in decks is determined differently. The bending moment is leading in this case. The quantity of reinforcement is in proportion with the bending moment in the construction and therefore in proportion with the load on the deck (M=1/8 ql^2). For solid flat slabs this comes down to 50 kg/m^3 prestressing and 75 kg/m^3 reinforcement (See Appendix L). The quantity of reinforcement and prestressing in the beam construction is determined by the reduction in force on the construction. These reductions concur with the results of the research done by A. Yee (Yee, 2007)

- *Load on viaduct is 4 kN/m.*
  According to Dutch regulation NEN 6702, NEN 6706 and NEN 6723 and ROBK-6 ((NEN 6702)(NEN 6706)(NEN 6723)(Rijkswaterstaat Bouwdienst, 2006). It is decided to calculate with traffic safety class 60. This is the heaviest class.

- *Only 1 type of foundation, prefab concrete piles*
  The most used foundations in the Netherlands are concrete prefabricated foundation piles. Because viaducts are usually built outside the built-up area, noise and other types of hindrance are usually not of big concern. Prefab concrete piles are therefore the most obvious foundation to choose. Other types of foundations could be applied but not much difference is expected from these variations. The foundation of the structure is mainly incorporated in to the model to show the effects of weight reduction on the foundation.

- *The structural elements are optimized.*
  The measures of the structural elements are optimized. This means that a column which has a certain dimension with C35/C45 concrete will have smaller dimensions when constructed in C53/C65 concrete.

- *Prefabricated elements are dimensioned on the final state.*
  During the transport of prefab elements a lot of force is put on the element. These forces are different than the forces that work on the prefab element during its function as load bearing element. Because of these extra forces, prefab elements sometimes need extra reinforcement. This is not included in the calculations.

- *A foundation slab is required underneath the columns, not underneath the abutments.*
  Appendix T displays there is only a foundation slab underneath the columns not underneath the abutments. This is incorporated in the tool

- *The dimensions of the foundation slab depend on the size of the foundation piles.*
  The foundation slab is the connection between the columns and the foundation piles. Assumed is that the dimensions of the slab are identical with each variant and will be poured onsite with C35/C45 concrete. The width of the slab is 5 times the width of the foundation pile; this means two foundation piles can be placed next to each other. The height of the foundation slab is half of the width.

6.2.3. Site assumptions

- *The size of the site office is the same for each project; the time of the project depends on the numbers of man-hours.*
  A big contributor to the emission onsite is the site office. It is assumed that the size of the building does not depend on the type of work. The duration of the project depends on the number of man-hours worked. The emission of the site office is linked to the number of man-hours.

- *There is always a crane available onsite, other equipment not.*
  On a construction site a crane is always on site, it is used with almost all operations onsite. Other equipment is not always necessary onsite.

- *The production capacity of the prefab factory is no bottleneck.*
  It is assumed that the production capacity of a prefab factory is of no influence on the emissions onsite. Although most prefab factories do not have the capacity to deliver a great number of beams at the same time, assumed is that this has no influence on the emissions.

- *Transport is no bottleneck.*
  The deliverance of raw materials to the (prefab) concrete factories and of construction material to the construction site is always on time. There is no time lost due to late delivery of materials or extra emissions due to lack of capacity in the prefab factory.

- *The energy required to produce prefab concrete elements is the same in Cat IV and Cat V.*
  There is no information available for the production of prefab elements "off the shelf"; the production process is more automated than the production process for project specific prefab elements. Because the production of Cat V prefab elements is more efficient, the energy requirement per m^3 produced concrete is the same.

- *Ground moving works are not incorporated in the tool*

  Ground moving works are more or less the same for each construction method. Because the quantity of ground moving works are very depended on measures of the structure and different design variables not incorporated in the tool. The ground moving works are not incorporated in the tool.

7. OPERATIONS OF THE QUICK SCAN TOOL

7.1. Introduction

The quick scan tool consists of a number of sheets. In order to gain insight in the process and to create a verifiable model this chapter explains the operations within the quick scan tool. To understand the tool completely it is necessary to use and research the model. This chapter shows the processes which lies at the foundation of the model. Each paragraph in this chapter discusses a different type of sheets. There are 5 types of sheets:

1. Input & output sheets
2. Intermediate calculations sheets
3. Emission and energy factors sheets
4. Calculation values sheets
5. Overview sheets

7.2. Global process

The global calculation process is schematized in Figure 7.1.

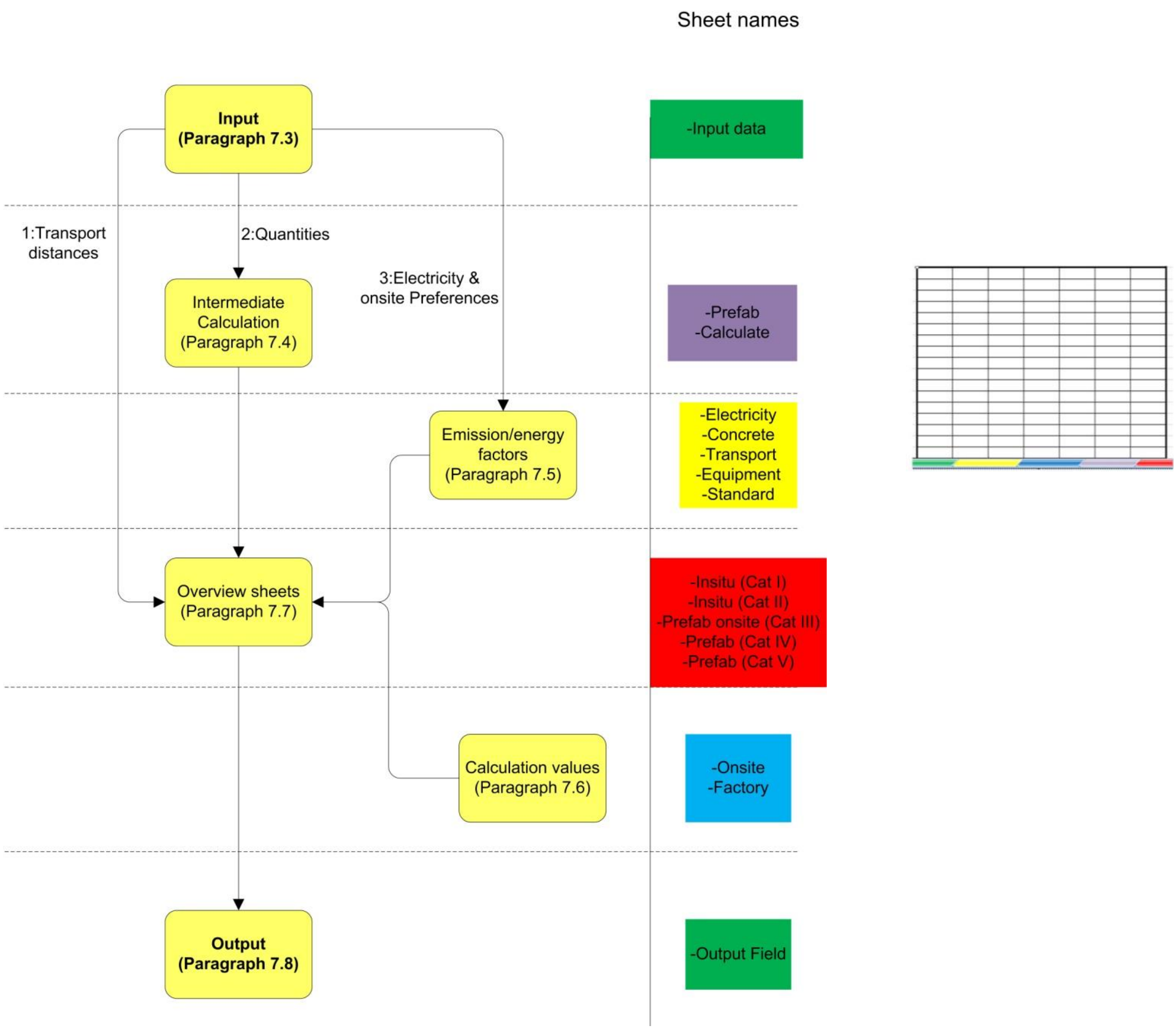


Figure 7.1: Overview of calculation process of model including sheet names (on the right a schematized overview of the excel is given)

Screenshots of the model can be found in Appendix R. In Appendix Q the model is discussed sheet by sheet.

7.3. Input

Figure 7.1 shows the structure of the model. Input data is entered in the tool, from there the data is used in various sheets. The input data is divided into 3 parts (see Figure 7.1).

1. The transportation distances are directly used in the overview sheets.
2. The quantities of construction material will first be recalculated for each specific construction method. After the quantities are recalculated they are used in the different overview sheets (Cat I-Cat V).
3. Electricity and onsite preferences are connected to the emission sheets.

For screenshots see page 88.

7.4. Intermediate calculations

These sheets recalculate the quantities of construction material for each particular construction method. Due to the use of different strengths of concrete and different deck constructions, quantities of construction materials vary. The information of the box beams are acquired from Spanbeton (Spanbeton).

For screenshots see page 99.

7.5. Emission and energy factors

The emission factors are determined partially by the input values and partially by pre defined emission factors. The sources used for the emission and energy factors are:

- ProRail (ProRail, 2009)
- Cement & Beton centrum(Cement & Beton centrum)
- Scope 3 analysis KWS(van Hattem en Blankevoort, 2010)
- DuboCalc(Rijkswaterstaat, 2010)
- Van der wegen(van der Wegen, 2008)
- SenterNovem(SenterNovem, December 2009)
- STREAM, CE Delft(CE Delft, 2008)
- BAM Project carbon Calculator(Koninklijke BAM groep NV, 2006)

For screenshots of the sheets see page 91

7.6. Calculation values

The calculation values are acquired from interviews. These values are special for Heijmans and are variable per company. The calculation values are used to calculate the construction time of each element and the number of hours the equipment is required.

For screenshots of the sheet see page 96.

7.7. Overview sheets

Introduction

The overview sheets combine all the information and add up calculations. The calculation of the emissions of a project is the sum of the emissions of the individual elements and the standard emissions of the site office and cranes. The overview sheets sum up the emission per category and per element. There is an overview sheet for each individual construction method and are named:

- Insitu (Cat I)
- Insitu (Cat II)
- Prefab onsite (Cat III)
- Prefab (Cat IV)
- Prefab (Cat V)

The difference in quantity of emissions is due to different construction methods. This influences the working hours, equipment hours and quantity of construction material. First the difference is discussed between the differences in calculation per element. After that the built up of the calculation is discussed.

For screenshots of the sheets see page 101.

7.7.1. Calculation per element

The structure can roughly be divided in 3 types of elements: Horizontal elements (deck), vertical elements (columns and abutment) and foundation. The emission of construction material and factory depend on the quantity of construction material. In the quick scan tool the differences in construction show in the calculations. This paragraph discusses the differences in construction process.

Horizontal element (deck)

Constructing a horizontal element (like a deck) insitu requires a support structure for the formwork. Prestressing is also required onsite. Besides the extra support structure and prestressing the built up of the emissions are the same as the emissions of the vertical elements. With the construction of prefab elements no support structure is needed.

Vertical elements (abutments and columns)

The operations of constructing the vertical elements insitu are composed of constructing formwork, placing reinforcement, pouring concrete and compacting concrete. The emissions of the construction material are linear with the quantity of construction material. The quantity of transport depends on the quantity of construction material, type of equipment required and number of working hours. There is one noteworthy difference between the construction of insitu columns and abutments, pouring columns creates high hydrostatic pressure in the formwork. Therefore the speed in which a column can be poured is limited to 1 m/h (Appendix L). This problem does not occur with the pouring of abutments.

With prefab construction not every element requires as much time to be placed. Placing a beam takes less time than placing a column, placing abutments takes the most time because a number of preparations are required before the element can be put into place.

Foundation

The emissions of the foundation can be divided in two parts; the foundation slab and foundation piles. The operations of the foundation slab are quite similar to the operations required for the construction of the vertical elements. The operations for the placing of the foundation piles are the same for each construction method. The quantity of foundation piles depend on the weight of and the loading on the structure.

7.7.2. Calculation per sector

Material

Construction material is the biggest contributor to the emission of CO_2 and consumption of energy. The quantity of concrete is calculated from the entered values from the input field and the factors calculated in the "prefab" and "calculation" sheet. Differences in quantities occur due to different types of concrete (C35/C45 or C53/C65) and different deck constructions (Solid flat bed or Box beam). The energy consumption and CO_2 emission of an element is composed of the quantity of material and type of concrete used.

People

Gives an estimate of the total number of man-hours required to construct an element. This is a combination of the time required to build the formwork, place the reinforcement, pour the concrete, crane time etc. These values are composed of calculation values acquired from interviews and measures from the input field. The total number of man-hours is not used as direct output but is used as input for other calculations.

Transport

Transport adds up all the transport required for construction. Transport can be divided in 3 parts:

1. Transport of construction material
2. Transport of people
3. Transport of equipment

1. The emissions of the construction material is composed of the distance a truck or ship needs to travel multiplied by the emissions of that particular transport mean per tonkm (a unit which describes the quantity of transport). The average loading of trucks and ships are incorporated in the emission values of transport.
2. The transport of people is composed of travel distance to their work (and return trip), the emissions of a car and the number of people in the car. The number of times people have to go to their work is the number of construction hours divided by 8, the number of working hours in a day.
3. The transport of equipment is composed of the travel distance to the construction site (and return trip) multiplied by the emission of transport in tonkm (CO_2/tonkm and MJ/tonkm).

Factory

The emissions in the factory can be divided in two parts.

- Emissions of the concrete factory
- Emissions of the prefab factory

Insitu constructions only have emissions from the concrete factory. Prefab constructions consist of emissions from both the concrete factory and the prefab factory.

The emissions of a concrete factory consist of the quantity of required concrete and the emission of the concrete factory per ton of the produced concrete. The emission per ton concrete depends on the type of electricity used.

Emissions from the prefab factory consist of the quantity of required concrete and the type of electricity used. As mentioned earlier the type of factory is not of influence on this value.

Onsite

Onsite emissions are composed of:

- Crane
- Prestressing equipment
- Concrete pump
- Compacting equipment
- Pile driving equipment

With prefab constructing the emissions are only composed of the emissions of the crane and pile driving equipment. Constructing a prefab deck solid deck (Cat IV) post tensioning is also required.

For screenshots see page 85.

7.8. Output

The output field consist of two parts; one numerical part and one graphical part. The numerical part shows the output of all energy and CO_2 required in a project. There is a distinction in five elements. Deck/beam, centre columns, abutment, foundation and standard. Each of these categories is again dived in five elements. Material, transport, factory, onsite and total. The purpose of this numerical part is to show (in absolute values) what the sum of emissions is. All elements are at least expressed in MJ and kg CO_2. Depending on the type of activity, there is also an expression in quantity of electricity or quantity of fuel consumed. To make comparisons between various construction methods, it is possible to compare two variants next to each other. The comparison is only possible in difference in construction methods. The second part of the output field shows the results in a graphical way. Multiple graphics are generated in the output field. An overview of the output field is given in Appendix P.

For screenshots of the sheets see page 89.

7.9. Recapitulate

There are 5 types of sheets defined in the tool. 1) The input and output sheet, will be used the most by the user. 2) The intermediate calculation sheet, calculates the quantity of construction material. 3) The emission and energy factors sheets, contains the hard data from the literature study. 4) Calculation value sheet contains calculation values acquired from Heijmans and provides input for number of work hours. Different calculation values are determined per construction method and per element. 5) The overview sheet, adds up all emissions, in this sheet all values are combined. The operations of the tool are per element and sector the same. Due to different calculation values the outcome per construction method is different.

8. RESULTS FROM THE QUICK SCAN TOOL

8.1. Introduction

To display the differences in CO_2 emission and energy consumption between different construction methods, a test case will be filled in the quick scan tool (QST). The only variable is the construction process. This chapter discusses the contribution of each element and each category. The next chapter discusses the role of different parameters in the model.

The QST is made to determine if there is a difference in energy consumption and CO_2 emission between different construction methods. It functions as a mean to answer the research question and not as the goal of this research. The outcome of the tool needs therefore to be placed in the right perspective. The results generated by the QST are not the exact emissions produced in the production and construction process, it shows mere the differences between the different construction processes and the relationship between them. The QST is especially valuable to determine the difference between construction methods in a certain project, or to judge the influence of a certain project parameter.

8.2. Input values

To display and discuss the output of the tool a test case is required to deliver input values. In this case; the project Randweg Eindhoven A2. Viaduct 15 (kw 15) is used as example in this research.

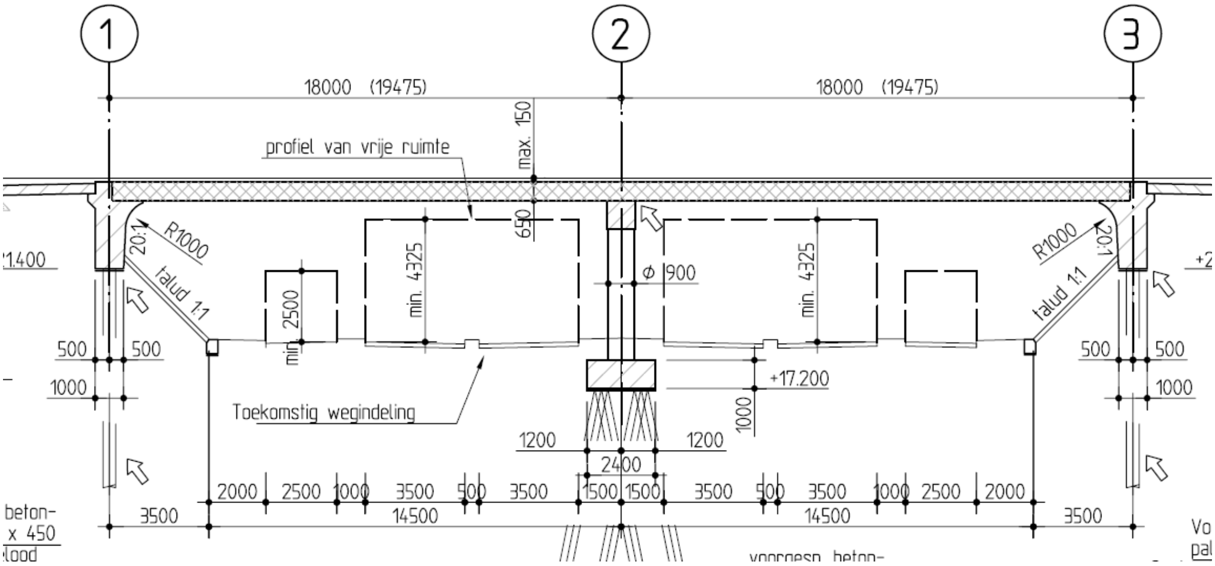


Figure 8.1: Overview of Viaduct 15

Figure 8.1 (see also Appendix T) shows the size of the structure. From the measures of the viaduct the quantities of construction material are determined. Transport distances are determined by suppliers of raw materials and construction materials in the Netherlands. The input variables which are put in the quick scan tool are shown in Table 8.1.

The values from load bearing elements are acquired from technical drawings of the structure (Appendix T). Transport distances are from actual cement, concrete and prefab factories. This ensures a valid and realistic comparison.

Project values		
Deck		
Quantity of concrete (deck)	388,8	m3
Surface of deck	648,0	m2
Length of deck	36,0	m
Column		
Quantity of concrete (per column)	3,18	m3
Number of columns	4,0	
Height of column	5,0	m
Abutment		
Quantity of concrete (abutment)	45,0	m3
Number of abutments	2,0	
Height of abutment	2,5	m
Width of abutment	1,0	m
Foundation		
Type of piles	Pile foundation (average)	
Number of piles	42,0	
Width of pile	0,45	m
Depth	18,5	m
Duration project	30,0	weeks
Transport		
Primary materials- concrete factory	100,0	km
Concrete factory- construction site	25,0	km
Primary materials-prefab factory	250,0	km
Prefab factory- construction site	150,0	km
Average travel distance car (to site)	50,0	km
Average number of people per car	2,0	people
Average travel distance car (to factory)	25,0	km
Type of car	Average	
Distance crane	50,0	km
Distance concrete pump	50,0	km
Onsite		
Electricity available	Yes	
Crane	Diesel	
Electricity		
Onsite	NUON	
Concrete factory	NUON	
Prefab factory	NUON	

Table 8.1: Input values for the test case

8.3. Results per category

The first results show the output as if a structure is built in only one category. The results are discussed briefly to get a rough idea of the difference in emissions of different construction methods. The next paragraph discusses the results per element. In Appendix R an overview is given of the complete output tables. Table 8.2 displays the total energy consumption and CO_2 emission of all the categories, if a viaduct was constructed in only one particular construction method.

Overview Total				
	MJ	Similarity	kgCO2	Similarity
Worst-case	2.135.000	100%	233.000	100%
Cat I	2.132.000	100%	230.000	99%
Cat II	2.110.000	99%	228.000	98%
Cat III	2.109.000	99%	228.000	98%
Cat IV	2.287.000	107%	257.000	110%
Cat V	1.636.000	77%	180.000	77%

Table 8.2: Overview of total energy consumption and CO_2 emission (in comparison with the worst case scenario)

Table 8.2 shows there is little difference between the emissions of Cat I-Cat IV. Cat V shows that there are considerable reductions possible when constructing with prefab "off the shelf". Figure 8.2 and Figure 8.3 show that the distribution of the energy consumption and CO_2 emission per category and sector. In Appendix X pie charts are displayed of the distribution of the energy and CO_2 per sector.

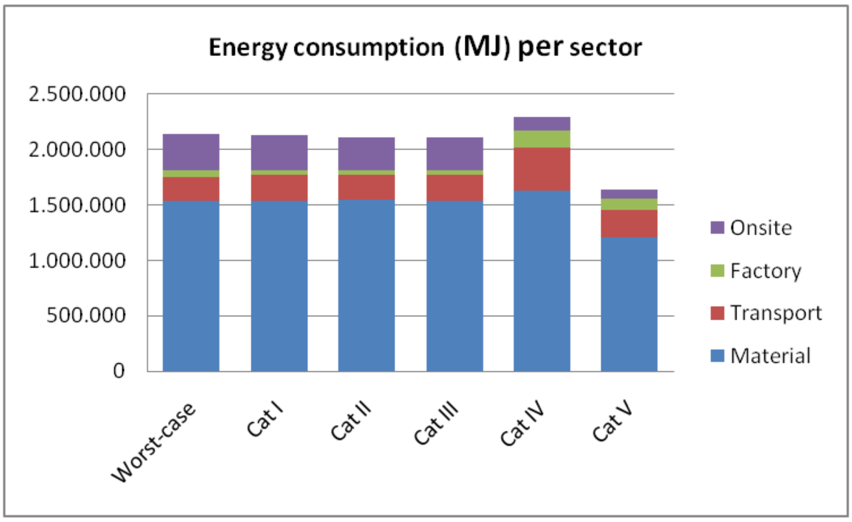


Figure 8.2: Energy consumption (MJ) during the production and construction of the test case

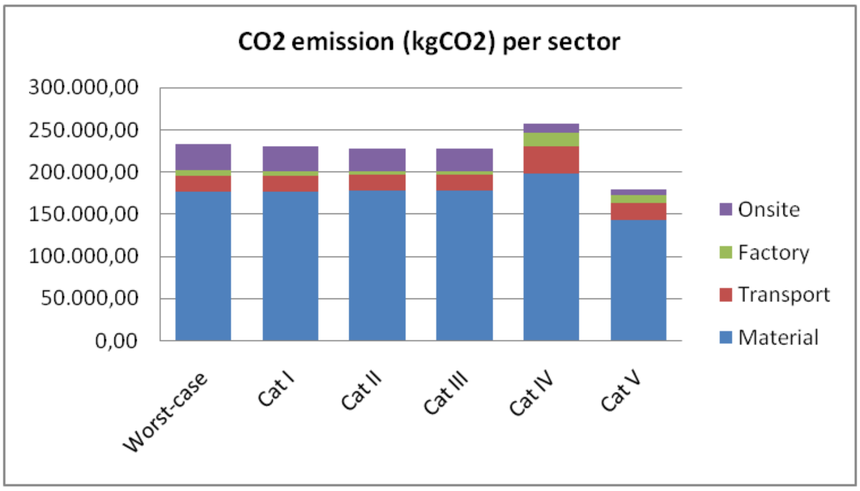


Figure 8.3: CO_2 emission during the construction and production of test case

From the appendices and figures it can be concluded that the distribution of the energy consumption and CO_2 emissions over Cat I- Cat III are roughly the same. There are only minor differences to be found in the distributions. About 74% of the total energy is used for the production of the construction material and 79% of the CO_2 output. Transport takes about 10% of the energy consumption and 7% of the CO_2 emissions. The factory 2% and the onsite emissions are roughly 12% of the total CO_2 emissions. The emissions of Cat IV and Cat V are distributed differently, because there is more energy required to produce C53/C65 and less energy is required onsite. The distribution shows therefore higher numbers on the material and factory part. The onsite emissions are lower; emissions from transport are higher because materials are transported over greater distances. The influence construction material has on the emission of a project is striking, but also predicted in the literature study. Comparing prefab and insitu construction methods it is clear that prefab has more emissions due to transport, because the prefab factory is not located on the travel route from the winning of raw material to the construction site. The emissions from the prefab factories are also higher than the emissions from the concrete factory. Onsite there is a clear difference between prefab and insitu construction. Emissions onsite are reduced significantly with the usage of prefab concrete.

From a first glance it seems there are considerable reductions possible (about 23%) when constructing in prefab (Cat V). In the next paragraphs it will be researched where these differences come from.

8.4. Results per element

Appendix V discusses each element individually and the difference which occurs when changing the construction method. In general it can be stated that between the analysed concrete structures no considerable differences occur. It is shown that prefab elements can reduce CO_2 emissions. The reductions in CO_2 emission of prefab consist of two factors, less CO_2 emission due to a reduction of construction material, and a more efficient process which contributes to a reduction in CO_2 emission. The relationship between the contribution of reduction of material saving and efficient process is different per element. The contribution, to the reduction of CO_2, of the prefab process varies from 13% (Deck/beam) to 55% (column) of the reduction per element. For more elaboration on this subject see Appendix V.

8.5. Conclusion

Analyzing the elements individually shows that reductions are possible when constructing with prefab. Constructing with high strength concrete has its downsides, because it uses more energy and emits more CO_2 per ton. If an element can benefit from this higher strength (in for example columns) then it is worth to use it. The reductions in emission onsite weigh up to the extra energy required in the factory and in transport.

Paragraph 8.3 shows that a reduction of 23% in CO_2 emission is possible when construction only with prefab "off the shelf". This reduction is greater than individual calculations of the elements would suspect. An overview is given of all the differences between the elements in Appendix W; the (weighted) sum of reductions (of the elements deck, columns and abutments) is given in Table 8.3.

There is a difference between the results of Table 8.3 and Table 8.2. The difference between the two sets of numbers comes from benefits that high strength concrete construction have. The reduction in weight of a box beam deck influences the force on the columns, abutments and foundation. The shorter construction time of prefab influences the quantity of electricity used by the site office. The next chapter discusses what the influences are of these effects.

	MJ	kgCO2
Worst-case	100%	100%
Cat I	100%	100%
Cat II	98%	99%
Cat III	98%	99%
Cat IV	115%	124%
Cat V	86%	89%

Table 8.3: Overview of total energy consumption and CO_2 emission (weighted average) (only deck, columns and abutments)

From Table 8.3 it can be concluded that there are no considerable differences between reductions in energy and CO_2 (expect from Cat IV).

9. SENSITIVITY ANALYSIS

9.1. Introduction

The previous chapter compares the emissions of different construction methods to a worst-case scenario. This chapter discusses which factors influence the outcome of the tool and thus research the factors which need to be influenced to reduce CO_2 emissions. The distribution of the emissions over the different scopes is discussed and the influence the results from the sensitivity analysis have on the shadow price. This chapter discusses mainly the reduction of CO_2 emissions for two reasons. 1) The previous chapter displayed no considerable differences occur between CO_2 emission and energy consumption. 2) Companies are more focussed on CO_2 emissions than energy consumption.

9.2. Sensitivity analysis

9.2.1. Set up

A sensitivity analysis is done to determine the contribution environmental friendly measures have on the reduction of emission of a project. The influence of the following factors is discussed

- Reduction of cement
- Reduction of reinforcement
- Green electricity
    - Onsite
    - Concrete factory
    - Prefab factory
- Weight reduction
- High strength concrete
- Project time
- Electric and diesel cranes
- Electricity onsite
- Transport distance
    - Raw material
    - Construction material
    - Equipment and personal
- Hybrid cars
- Carpooling
- Construction size
- Repetition

An overview of the influence of all these factors is given in Appendix AA.

9.2.2. Results per factor

The sensitivity analysis (Appendix AA) has shown that there are multiple factors which influence the emissions of a project. Some parameters influence the outcome of the tool more than others. There are eleven situations discussed which influence the project.

Cement and reinforcement

The sensitivity analysis shows that great reduction can be obtained when reducing both cement as well as reinforcement. Although 25% reduction is not likely to, it displays the impact construction materials have on the emissions of a project. Further research on how to reduce construction materials is therefore very interesting. For both cement and reinforcement there are two obstacles to overcome in reducing construction materials: structural feasibility and legal feasibility.

Green electricity

The influence of green electricity has its benefits, and can influence the output of the emissions of a total project to about 4%. When the emissions onsite are considered, a reduction of about 20% can be obtained. When green electricity is combined with (electrical) tower cranes emissions can even be further reduced. These types of reductions are very interesting for a contractor, because it shows the influence a contractor has on the emissions of a project.

Weight reduction

Weight reduction influences the emissions during the production and construction of a structure. A lighter deck means lighter columns, lighter abutments and a lighter foundation. The sensitivity analysis shows a reduction of 20% on the emission of columns and abutments can be obtained by constructing a lighter deck. A reduction of 26% in the emissions of the foundations can be obtained by constructing a box beam deck. This shows the influence design choices and choices the material have on the emissions of a project. On the emissions of a total project the emissions can be reduced with about 15% when a hollow deck is used instead of a solid flat slab.

High strength concrete

Considering the influence of the usage of high strength concrete with regard to transport, factory and onsite emissions in general it can be stated that the usage of high strength concrete is justified, because there are less emissions throughout the whole production process. Less CO_2 is emitted due to less material, transport and in the factory. High strength concrete should only be used if structural gain is acquired.

Site office

Different construction methods have different production times. Onsite there is always a site office, which needs lights, heating and electricity. The total construction time therefore influences the emission of a project. Decreasing the construction time by using more equipment does not have a significant benefit.

Cranes

From an environmental point of view (electrical) tower cranes have a big advantage. Tower cranes are more energy efficient than diesel cranes. An important factor is that the energy supplier can be selected by the construction company, if green electricity is used instead of grey electricity, the emission can be reduced even further. These factors added up mean that reductions can be obtained onsite. Whether or not it is functional to use tower cranes depend on the project and the size of the project site. General foremen prefer to use diesel cranes, because they are more easily deployable, and are easier to work with onsite. Which types of cranes is a choice that needs to be made by the project team.

Availability of electricity

The availability of electricity influences the output of CO_2 in the project because working with generators is less efficient than using power right of the grid. The total emissions onsite can rise with about 8% if there is no electricity onsite. This is between 1% and 4% on the total emission of a project.

Transport distance

Reducing transport distances is a factor which is important to keep in mind when researching ways to reduce CO_2 emissions. Both the supplier of raw material and of construction material need to be closely review and resources should be obtained as close to the project as possible. Especially when constructing with prefab elements should this be kept in mind. The influence of transport distance of equipment and personal is of less influence.

Hybrid cars

The implementation of hybrid cars and carpooling also reduces the emissions of the project. The contribution reduction on the whole project is rather small.

Construction size and repetition

The size of a construction and the number of repetitions has influence on the emissions of a project. Some construction methods benefit more from this than others because of the reuse of formwork. With prefab construction the size of the elements does not influence the emission of a structure, but the number of elements does.

9.2.3. Results overview

Appendix AA discusses the influence each investigated factor has on the emission of a particular sector. This paragraph discusses the influence each of these factors on the total emissions of the project. In previous chapter and in Appendix AA it is that the insitu construction methods as well as prefab construction methods do not differ much. Therefore only one insitu construction method (Cat I) and one prefab construction method (Cat V) is discussed.

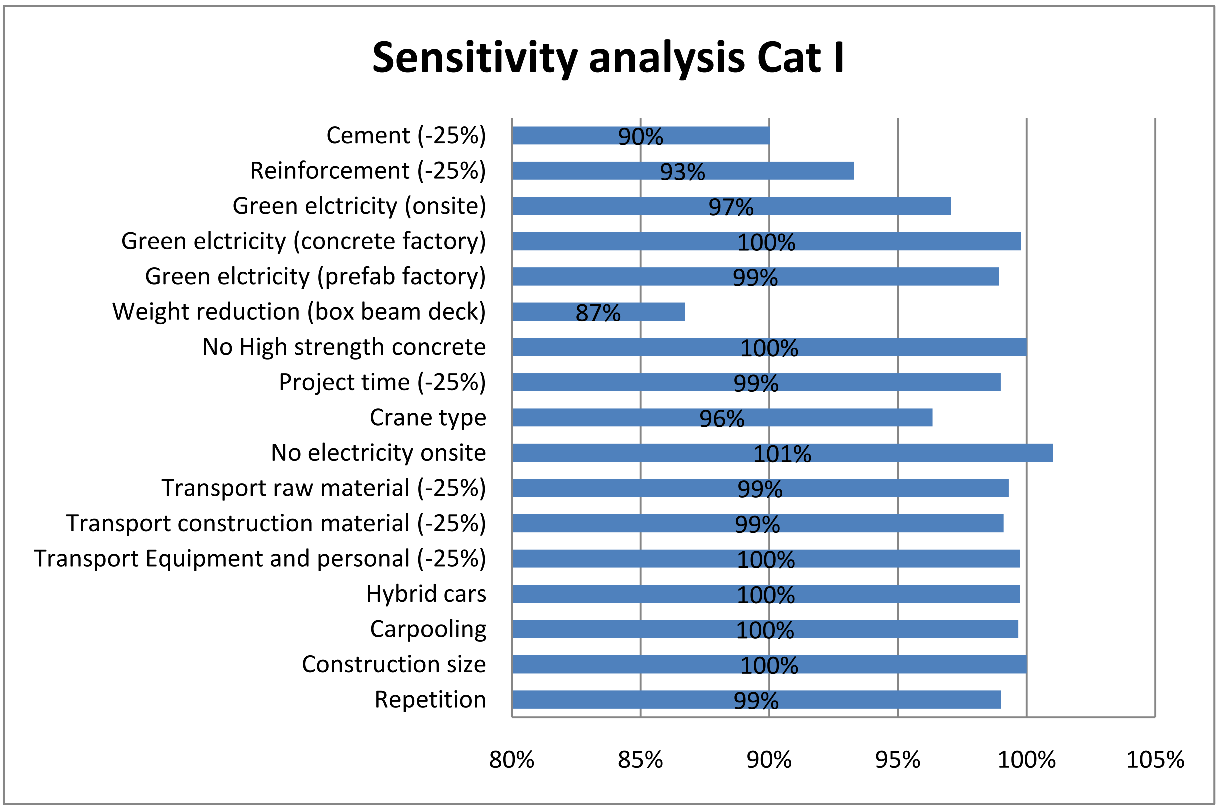


Figure 9.1: Sensitivity analysis (Cat I)

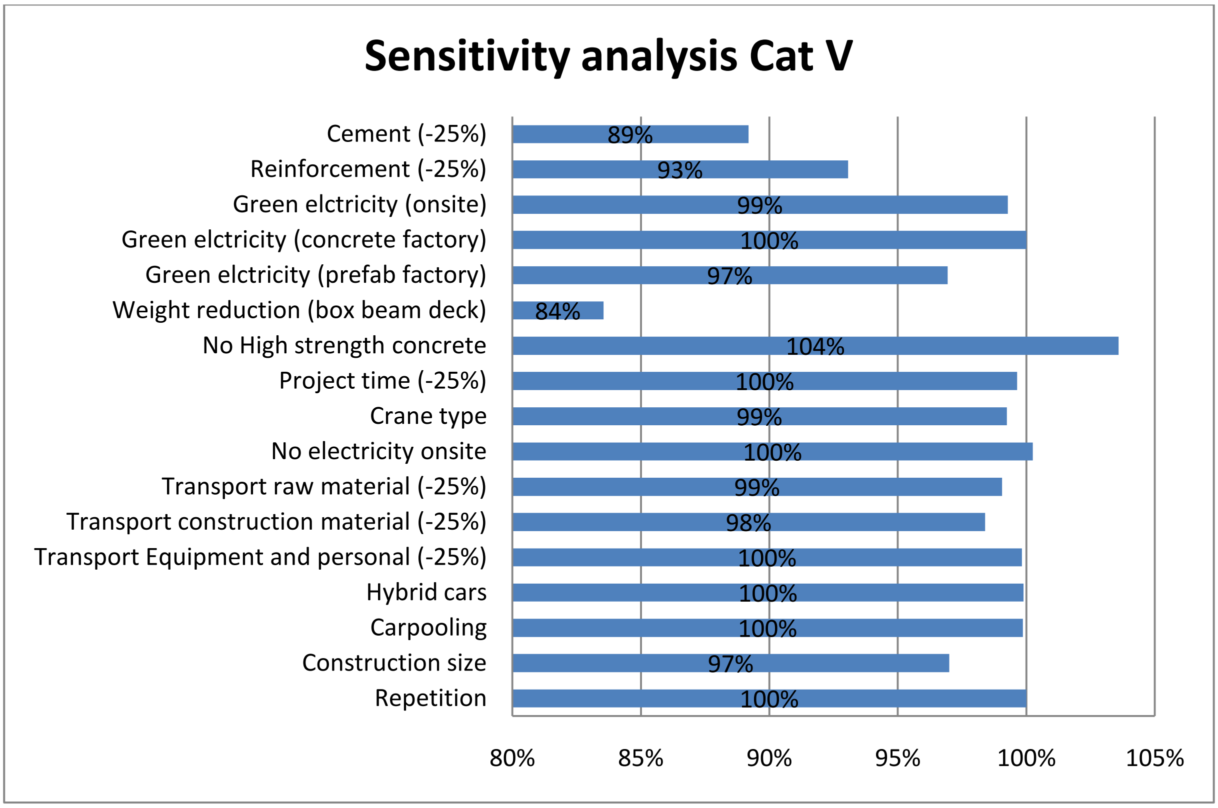


Figure 9.2: Sensitivity analysis (Cat V)

Figure 9.1 and Figure 9.2 show the results of the sensitivity analysis. The results of both sensitivity analyses are reasonably comparable. The biggest reductions are obtained from reducing total weight of the structure by constructing a deck with box beam girders. This has a positive effect on the load bearing elements of the construction. Other important reductions can be obtained by reducing the quantity of cement and concrete. The application of green electricity and different cranes also has considerable influence, especially because both implementations amplify each other. The decrease in transport distance of raw material and construction material should also be incorporated as factor to reduce emissions. With the purchase of prefab elements the selection is made based on price not on transport distance. Great detours often occur with the production of prefab elements.

There is a slight difference in the results of the sensitivity analysis of the insitu and prefab construction method. The influence of weight reduction on the emission of a prefab structure is greater than on an insitu structure. This is mainly due to the fact that the emission of a deck to the total emission of a project is more considerable in prefab (57%) compared to insitu (49%). The sensitivity analysis also shows that the high strength concrete has a positive effect on the emissions of a project. Insitu concrete construction profits more from switching to electrical cranes than prefab construction; because more crane hours are required.

9.2.4. Comments on results

The results of the sensitivity analysis need to be put in a right perspective to be of value. Reviewing each part of the analysis separately shows some proposed reductions are easier to accomplish than others. Some options are multiple choice while other comparisons lower the values by a certain percentage. The previous paragraph showed that reducing the quantity of cement and reinforcement with 25% would greatly reduce the emissions in a project. A reduction of 25% is probably hard to obtain, but the result show that it is an important area that needs more research. Reducing the quantity of cement and reinforcement in concrete elements has two main problems; 1): Structural feasibility, reducing the quantity of cement and reinforcement in concrete influences the structural characteristics of the concrete it needs to be researched whether or not this is save. 2): legal feasibility, there are minimum legal quantities of cement and reinforcement which concrete elements should contain. Construction regulation should be changed in order to make reductions possible. In Appendix C it is displayed that the Netherlands has a very low quantity of clinker in its cement and with the production of cement much alternative fuels are applied. This makes the Netherlands one of the leading countries in this field. The reduction of cement in concrete is therefore even more important for other countries than for the Netherlands. Important breakthroughs could be achieved if there is an increase in focus on reducing the quantity of clinker in cement and implementing more alternative fuels in the process.

The transport distance of prefab elements can be easily influenced by contractors and (prefab) concrete companies. In the test case the transport distances in insitu is much less than in prefab. Reductions greater than 25% can therefore be achieved. For example: In the test case, raw material is produced in Limburg the prefab elements are produced in Koudekerk aan den Rijn and then transported to Eindhoven. If the elements would be produced near Eindhoven (in for example Son), there would be a decrease in transport distance of raw material of 60% and construction material of 66%. The influence of the reduction in transport would therefore be more considerable on the total emissions of the project.

Although the research has focussed on the construction of viaducts, a large quantity of the results of the research will be applicable to other civil engineering structures. A viaduct consists of a foundation, columns, abutments (vertical elements) and a deck (horizontal elements). Other civil engineering works will also consist of (a number) of these elements. The conclusions drawn from the research will therefore be applicable to other civil engineering structures.

9.3. Best case

Appendix AA discusses which factors influence the emissions of a project. By changing the variables in to the best possible setting a total reduction of 43% can be obtained in comparison with the worst-case scenario. The best-case situation is a structure constructed solely from "off the shelf" prefab. Reinforcement and cement are reduced by 25%. Green electricity is applied in the prefab factory and onsite. Electrical cranes are used onsite, workers carpool with 4 people and use hybrid cars. All travel distances are reduced by 25%. Table 9.1 shows the difference in emission between Cat I and Cat V.

Best case	kg CO2	Similarity
Worst-case	233.000	100%
Cat I	230.000	99%
Cat I (best case)	160.000	69%
Cat V	180.000	77%
CatV (best case)	133.000	57%

Table 9.1: Similarity of emissions between worst-case and best-case

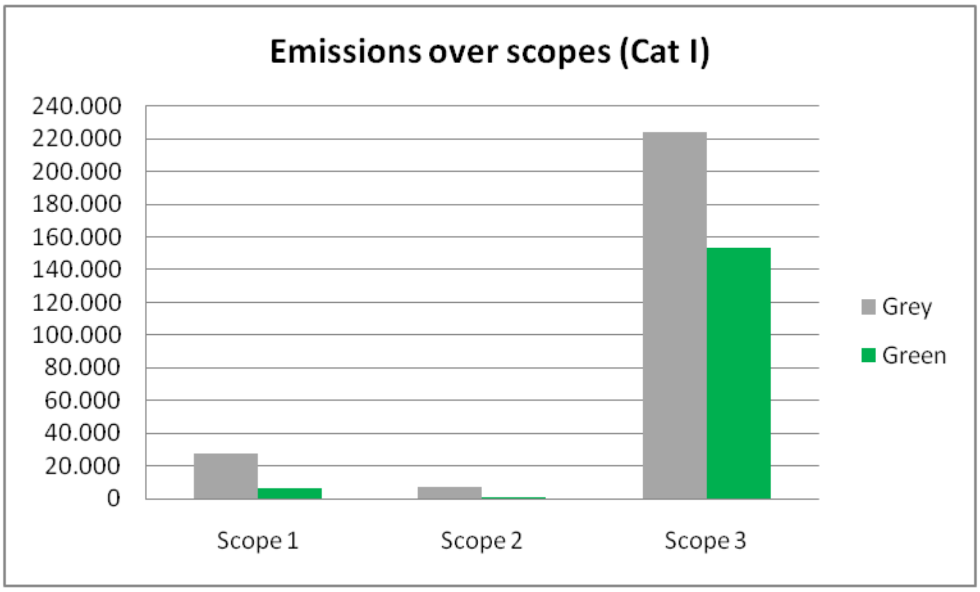
Some of the factors discussed in the sensitivity analysis are more easily achieved than others. Concerning prefab (Cat V) it is important to realize that 23% of the reduction is realized by changing construction method. With insitu the influences of the CO_2 reducing measure are more significant than prefab. From the total reduction of 31%, 30% of the reduction is due to green initiatives. These differences considered it can be concluded that taking construction methods into account is advisable when reducing CO_2 in construction. The influence of the prefabrication process in combination with high strength concrete reduces the emissions considerably. The reason that the influence of the green measures are of less influence on prefab than on insitu is because this research is focused largely on onsite emissions. To find reductions in the prefab process, more focus should be on the prefab process.

9.4. Emissions according to GHG protocol

The distribution of the emissions over the different scopes is given in the following figures. As can be concluded, there are less emissions in scope 1 and scope 2 when constructing prefab elements. The emissions onsite are smaller with the usage of prefab, the construction time is also shorter. If a construction company wants to reduce its own emissions, shifting the construction process to more prefab reduce the emissions of a construction company (scope 1 and 2) and the emission of the total project. The implementation of green electricity onsite or using hybrid cars and types of cranes affects the emissions in scope 1 and 2. This is displayed in Figure 9.3. Appendix BB displays the findings of the sensitivity analysis over the different scopes; it shows that the absolute reductions are largely found in scope 3. The relative reductions considered, the emissions in scope 1 and 2 are reduced the most (Table 9.2).

	Similarity		
	Scope 1	Scope 2	Scope 3
Cat I	21%	5%	68%
Cat V	40%	5%	76%

Table 9.2: Similarity of CO2 emissions between test case and best case, divided over scopes



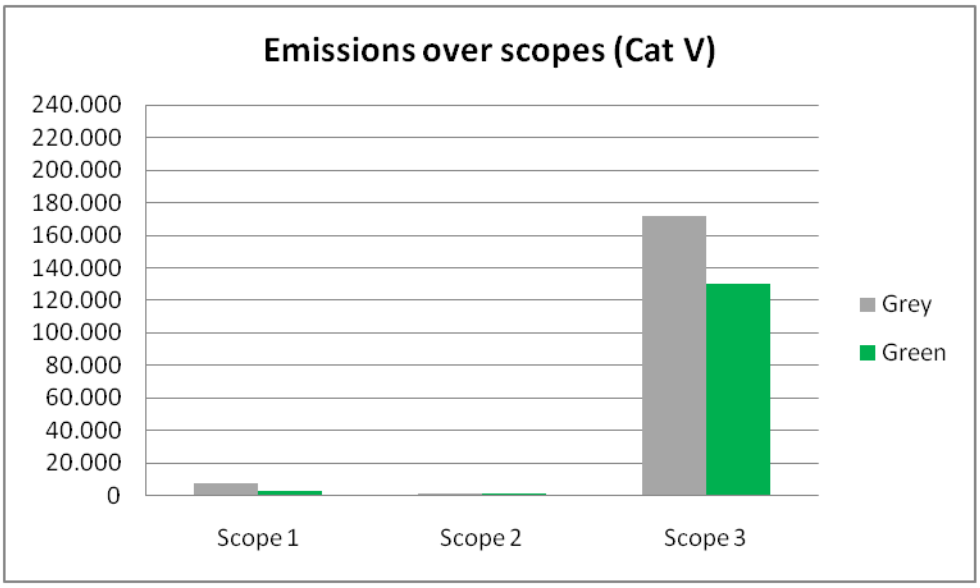


Figure 9.3: Overview of emissions in different scopes and the difference when green measures are implemented

9.5. Shadow prices

A well known concept of giving value to the cost of CO_2 is shadow pricing. A value is given for every ton CO_2 that is emitted. Therefore the environmental cost of a project can be calculated to a price. CE Delft has calculated the price of CO_2 to €25,-/ton (CE Delft, 2010). For the whole project the difference between the worst-case (233 ton) and best-case (Cat V) is (133 ton) 100 ton. This 100 ton resembles a difference in shadow price of only €2500,-. This is a small price considering a whole project. Construction companies could therefore consider taking shadow pricing into their tender compensate the CO_2 emissions. It is expected that the shadow price of CO_2 will increase in the future. The value of emission of CO_2 is constantly revaluated. In previous years the shadow price per ton CO_2 was €50,- per ton. The willingness of a company to reduce CO_2 emissions is greatly affected by the price of CO_2, when this price increases companies are likely to reduce more CO_2.

9.6. Conclusion

CO_2 emissions can be reduced by choices made by a project team. Comparing the worst-case scenario to the best case shows that the influence of "green measures" depends on the construction method. The most considerable reductions are obtained by reducing the weight of the structure, using high strength concrete and reducing the quantity of cement and reinforcement. The influence of implementations of green electricity, electric cranes, and hybrid cars, are smaller, but can result in a considerable reduction in the emissions of projects constructed in insitu. When constructing with prefab, the emissions are less influenced by the implementations of "green measures". It needs to be emphasized that some measures are more realistic to be accomplished than others.

Construction Company

Considering the point of view of a construction company, the implementations of hybrid cars, electrical cranes and green energy have a large influence on the emissions of scope 1 and 2. This means that a company can reduce its own CO_2 footprint by these measures. Considering the bigger picture, the reductions made possible by changing to another construction method are much more considerable.

10. DISCUSSION ON EMISSION FACTORS AND CALUCLATION VALUES

10.1. Introduction

The research on CO_2 emissions is still in an early stage and discussions are going on about which emission factors and scopes should be applied. The quick scan tool uses values based on a number of sources. This chapter discusses these values and compares them with other values found in the literature.

DuboCalc

The government has recently released a tool to calculate the environmental impact of a structure. This tool is called DuboCalc. DuboCalc calculates the LCA of a civil engineering structure and includes, among other things, waste production, toxicity, energy and smog. A CO_2 calculation is included also. DuboCalc is developed from a different point of view than the quick scan tool.

There are 3 important differences between the QST and DuboCalc: 1) DuboCalc makes no difference between prefab and insitu concrete construction. 2) Emissions due to transport and construction time are set as variables in the quick scan tool; in DuboCalc these are assumed values. 3) DuboCalc is not only focussed on the CO_2 emissions and energy consumption of a project, but also on the environmental impact of a project in a much larger sense. The values used in DuboCalc will function as the start point of the discussion about differences in calculation values. Version 1.12 (Beta) of DuboCalc is used as reference. This is one of the first released versions of DuboCalc, from the release on there has been a number of new versions. This comparison put the outcome of the tool into perspective. There has not been made a one-on-one comparison because, as the chapter will show, the differences between the two tools are too large.

Overview of chapter

First differences in scopes and assumptions are discussed. After that a comparison is made between the emission factors used in QST and DuboCalc. The chapter is finished with a conclusion.

10.2. Scope and assumptions and available data

10.2.1. Scope and assumptions

Calculating emission factors require a well defined scope and assumptions. Which elements should be incorporated in a research differs from person to person, especially when determination of emission factors. In published research these are often not clearly defined, clearly communicated or consequently applied.

10.2.2. Data

Researchers often depend on information provided to them by other parties (private companies, other research institutes). Data acquired by third parties is often incomplete or not within the set scope of a research. Available data is sensitive on which location it is measured, this differs from factory to factory and from site to site. This results in incomplete researches or researchers which are debated.

10.2.3. Activities

From DuboCalc it becomes clear that there are no special values incorporated for the production of prefab, the transportation of labour to the factory and construction site and no values are incorporated in DuboCalc for prestressing. Prestressing is assumed to be done by (only) labour. There is no process mentioned in DuboCalc which is not incorporated in QST.

10.2.4. Work-hours

The basis of all CO_2 emissions and energy consumption onsite and in the factory lies in required working hours. Required working hours in the QST are based on values Heijmans has acquired over a number of years. These numbers can differ from project to project, and company to company. DuboCalc makes no clear distinction in man-hour but in calculates with hours equipment need to operate. DuboCalc incorporates in its calculations the inefficiency of trucks for unloading. Comparing work hours between DuboCalc and QST is difficult because different units are used.

10.3. Emission factors

10.3.1. Electricity

Emission factors used in the quick scan tool for the electricity are derived from the "CO_2-prestatieladder" from ProRail (Prorail, 2009). The values from the "CO_2-prestatieladder" are provided by CE Delft (CE Delft, 2008). CE Delft is a Dutch research bureau which specializes in environmental research. The sources of the emission factors found in DuboCalc are not clear; a fair guess would be that the values are acquired from the research bureau of the government. Table 10.1 shows an overview between the differences in values used in the quick scan tool and DuboCalc.

	Value Quick Scan Tool	Value DuboCalc	Similarity
	kg CO2/kWh	kg CO2/kWh	
Electricity (grey)	0,495-0,65	0,805	61%-81%%
Electricity (green)	0,015-0,3	0,1296	12%-231%
Hydro electricity	0,015	0,11	14%
Solar electricity	0,08	0,15	53%
Wind electricity	0,015	0,15	10%

Table 10.1: Overview of values used in quick scan tool and DuboCalc

There are significant differences between the values used by DuboCalc and the quick scan tool. Especially the emission factors of green electricity. The origin of these differences is not clear, but a reason for this difference could be a difference in scopes of the researches.

Besides the difference found in the values used in the quick scan tool and DuboCalc, the question arises whether or not green electricity is as green as stated in the figures. Objections to green electricity projects vary from, landscape pollution to loss of habitat for animals. The gain of green electricity therefore is influenced by the opinion of the researcher. Even though this discussion is not within the scope of the research these comments are worth mentioning.

10.3.2. Material

The production of construction material is the largest contributor to CO_2 emissions in the production and construction of projects. The emission factors used in the quick scan tool are acquired from Cement & Beton centrum (Cement & Beton centrum). The values used in DuboCalc come from the international steel institute and the Dutch government (Rijkswaterstaat). Table 10.2 displays the different emission factors.

Processes	Value Quick Scan Tool				Value DuboCalc				Similarity	
	MJ/[Unit]		kg CO2/[Unit]		MJ/[Unit]		kg CO2/[Unit]		MJ	kg CO2
Concrete C35/C45	1051	m3	154	m3	1070	m3	168	m3	98,25%	91,92%
Concrete C53/C65	1403	m3	222	m3	1430	m3	262	m3	98,13%	84,56%
Reinforcement	9000	ton	714	ton	20400	ton	1820	ton	44,12%	39,23%
Pretension steel	9000	ton	714	ton	22800	ton	2000	ton	39,47%	35,70%

Table 10.2: Comparison between emission factors used in quick scan tool and DuboCalc for material

The production values used for concrete compare reasonably well with each other. Although a difference of 15% (C53/C65) is substantial.

Reinforcement

As example the emission factors of reinforcement steel are discussed. Both values only include the production, transportation and installation is not included. Because these values differentiate considerable from each other extra sources are consulted. Bouwen met staal, the Dutch association of steel constructions provides values of 480 kgCO_2/ton for construction steel (heavy usage) to 960 kgCO_2/ton (light usage)(Bouwen met Staal, 2003). Bouwen met Staal under scribes the considerable variations found in CO_2 emission values. Construction companies use values between 1000 kgCO_2/ton (Koninklijke BAM groep NV, 2006) to 1060 kgCO_2/ton (transport included) (IPCC, 2006). Van Hattem en Blankevoort state that:" Reinforcement is not taken into account because data contain big variations, and raw input data is scarcely available (van Hattem en Blankevoort, 2010). The opinion of van Hattem en Blankevoort is a suitable conclusion on this subject, it is not totally clear which values are best used. The quantity of energy required to produce steel and concrete are heavily debated parameters.

The differences in this case occur due to lack of availability of raw data as is under scribed by Bouwen met staal and van Hattem en Blankevoort. Difference between factories, efficiency and energy supply contributes to these uncertainties. Transportation and location is also of influence on the calculation value.

10.3.3. Equipment

The emissions onsite depend on a number of factors, the type of equipment, the power of the equipment (and its particular emissions), the time it works and its efficiency. In the quick scan tool most of the emissions are gathered from the project carbon calculator (PCC) (Koninklijke BAM groep NV, 2006). The PCC contains a large database of emissions of equipment; when no information was available from the PCC, additional information was acquired from a number of resources. Table 10.3 compares the emission factors of PCC and DuboCalc.

Processes	Value Quick Scan Tool				Value DuboCalc				Similarity	
	MJ/[Unit]		kg CO2/[Unit]		MJ/[Unit]		kg CO2/[Unit]		MJ	kg CO2
Equipment										
Concrete Pump	540	h	46,12	h	8890	h	672	h	6,07%	6,86%
Compacting concrete	1,18	m3	0,2	m3	8,36	m3	0,65	m3	14,11%	30.86%
Crane	720	h	53,23	h	1090	h	82,8	h	66,06%	64,29%

Table 10.3: Comparison between values quick scan tool and DuboCalc

Crane

The quick scan tool calculates with the emissions of a 100t crane. DuboCalc uses a "heavy crane", although not clearly what the weight of the crane is, there are cranes available which go up to 200t (or more). The differences in cranes could explain the difference in emission.

Compacting

There are considerable differences in the emissions of compacting concrete. The value used, for compacting concrete, in the quick scan tool is derived from a scope analysis of KWS (van Hattem en Blankevoort, 2010). KWS has outsourced these calculations to INTRON, an independent consultancy firm which is familiar with these calculations. The information in DuboCalc comes from the Dutch concrete database. The origin of the difference between the two values is not clear. DuboCalc does not take into account any energy for pretension.

Concrete pump

The size and productivity of the pump are important parameter in the emissions of a concrete pump. The information in the quick scan tool is again derived from the PCC; the information in DuboCalc is acquired from INTRON. The QST calculates with a 35m+jib concrete pump with a (effective) capacity of 50 m^3/hour. If the capacity would be doubled still substantial differences would be found. The data from DuboCalc does incorporate transportation, in the quick scan tool this is a separate factor. The difference found in both emission values are not explained by this.

Foundation

The emissions of the construction of a foundation depend on; soil conditions, depth of the foundation and used equipment. The quick scan tool uses only one type of ram (hydraulic ram with power pack). DuboCalc uses more than one type of ram.

Table 10.4 shows the differences between the different types of rams, the foundation method which resembles the closest the power pack is the hydraulic ram. The numbers show that the assumed values in the quick scan

tool are almost twice as high as assumed in DuboCalc, it is hard to make a definite statement about the values, because it is not clear what rate of construction is used in the calculations of DuboCalc.

	Value Quick Scan Tool		Value DuboCalc	
	MJ/h	kg CO2/h	MJ/h	kg CO2/h
Power pack	1090 h	88,2 h		
Hydraulic ram			2276,57 h	170 h
Diesel ram			1180 h	89 h
Electric ram			310,4 h	23,2 h
Ram (average)			828 h	71 h

Table 10.4: Comparison between different rams

There are multiple ways to construct a foundation, in the quick scan tool only one type of foundation is incorporated.

10.3.4. Transportation

The emission factors assumed in the quick scan tool for transportation can be divided in three parts; the transportation of people, materials and equipment. The transportation of people is based on the assumed working hours, general occupation rate and travel distance. The emissions of the transport of materials are based on occupation rate and efficiency of transport (detours, empty runs). These values are acquired from STREAM (CE Delft, 2010), and the emission factors are determined by ProRail (effectively also CE Delft). DuboCalc uses calculation values from 1995(source unknown) for transport of construction material. The values applied in DuboCalc are not entirely clear because assumptions are made about travel time and waiting time, which are not clearly articulated.

DuboCalc includes no emission for transportation of people and equipment to the construction site. Again it is clear that different calculation values are used, with different sources and different assumptions.

10.4. Conclusion

There are considerable differences between available emission factors and calculation values. The difference between values provided by “reliable” resources is remarkable. The emissions of transport and equipment onsite depend on factors like worked hours, type of equipment, efficiency of applied equipment and types of task.

Used scopes

The origin of the problem lies in the number of researches available, the scope and assumptions made in the research and available data. The determination of these calculation values contains many different variables. Remarkable is that acknowledged companies, like CE Delft and Rijkswaterstaat, come with such a different emission factors. The difference in scope used by research institutions is hard to determine individually. These uncertainties form the bases for the problems around calculations on CO_2. There has not yet been set clear guidelines on how to determine emission factors makes it hard to determine a precise value.

Different sources

It is remarkable to see the number of sources used by both the QST and DuboCalc. These sources are applied (seemingly) random in the tools. DuboCalc for example, uses in the calculation of concrete, 5 different sources, for every process a different source. 1 source for the emission on the material concrete, 1 source for the transportation, 1 source for the concrete pump, 1 source for the crane and 1 source for the compacting of the concrete. Using multiple sources enlarges the uncertainties in the outcome of a tool and makes it hard to value the outcome of the tool.

Influence of uncertainties

The influence of the uncertainties in emission factors is hard to determine. If more CO_2 is emitted due to the production of construction material this is in favour of prefab construction method. If equipment has a lower emission factor than assumed in the QST this is in favour of insitu construction. The differences between DuboCalc and the QST are apparent. The discussion on emission factors results in the QST (in the first place) cannot be used to calculate the emissions of a project, but provide insight in the factors that influence the emissions of a project.

Researching and determining correct emission values is not a goal in this research; it is however import to discuss the subject to put the result of the research into perspective. The implications different calculation values have on the sensitivity analysis is hard to determine. The quantity of emissions will change, but the qualitative conclusions will probably stand.

11. CONCLUSIONS AND RECOMMENDATIONS

11.1. Conclusions from research

11.1.1. Research organisation

Research topic

There has been an increase in attention to minimizing CO_2 emission in the construction industry. This research focussed on the question whether or not there is a difference in CO_2 emission and energy consumption between prefab and insitu concrete structures and which factors influence the emissions of a project.

The quick scan tool

A tool (the quick scan tool) has been developed to calculate the differences in CO_2 emission and energy consumption between different construction methods. The quick scan tool makes a comparison between 3 insitu construction methods traditional formwork (traditional formwork (Cat I), system formwork (Cat II) and prefabrication onsite (Cat III)) and 2 prefab construction methods (project specific formwork (Cat IV) and "off the shelf" prefab (Cat V)). The quick scan tool categorizes emissions in 4 different sectors:

- Material
- Transport
- Factory
- Onsite

11.1.2. Results from the tool

Results

Prefab concrete viaducts will, in general, use less electricity and emit less CO_2 than insitu concrete structures. Constructing with prefab reduces emissions up to 23% in comparison with the worst-case scenario, for insitu construction this is only 2%. The difference in emissions originates from three factors:

1) The production and construction process of prefab concrete viaducts is more efficient; the emissions onsite are reduced considerably by constructing with prefab.
2) Prefab concrete uses high strength concrete, reducing the overall required quantity of concrete, which has a direct positive effect on the emissions of a project. The reduction of construction material also has a positive effect on other structural elements.
3) Constructing a prefab deck with box beams reduces the weight of the structure and the size of the structural elements

The differences in CO_2 emissions between insitu and prefab viaducts are also valid for other civil engineering structures. The research has showed that the prefab process is more efficient than the insitu process for both vertical and horizontal load bearing elements.

Outside the research scope there are more reasons why prefab has environmental advantages. These advantages include better waste management, high production quality and improved control on construction time.

Difference between construction methods

From the research it can be concluded that there are no noteworthy differences in the emission between the reviewed insitu construction processes. The differences in the processes are too small. Between the reviewed prefab constructions methods there are noticeable differences. A prefab deck constructed with box beams (Cat V) requires less construction material than a solid prefab deck (Cat IV). The lighter deck influences the rest of the structure. The CO_2 emissions of the vertical load bearing elements constructed in both prefab construction methods are comparable.

Sensitivity analysis

The sensitivity analysis demonstrates that the largest gains in reducing CO_2 emissions are accomplished by constructing as light as possible and reducing the quantity of required cement and reinforcement. Optimizing transport distances as well as implementing green electricity and electric cranes also have noteworthy influence on the reduction of CO_2 emissions, but are less considerable. Other environmentally friendly measures, like hybrid cars and carpooling have less influence. The conclusions from the sensitivity analysis are also applicable for other civil engineering works.

Emission factors used in the tool

There are numerous emission factors available; because different scopes and calculation values are used it is hard to value these factors. In tenders a tool is required that is agreed on by multiple parties, therefore the values calculated by the quick scan tool need to be put in the right perspective. A great advantage of the tool is that insight is acquired on how different construction processes are influenced by choice made by the project team.

11.2. Recommendations

11.2.1. Future research

Research should focus on minimizing construction weight and reducing construction material. Reducing cement in concrete mixtures is another field which could contribute considerably to the environmental problem as well as research into replacing CEM I cement in high strength concrete.

The process of winning raw material is omitted from this research, as well as production of cement and reinforcement. Researching possible reductions in factories contributes to a more complete understanding of the production process and could produce ideas on how to reduce emissions in factories.

11.2.2. Government

Application in tenders

In the author's opinion, the government has two possibilities to reduce CO_2 emission in a construction project.

1) Set clear guidelines: Because CO_2 is affecting the environment there should be a clear legal framework defining the allowable emissions. Such frameworks already exist for emissions of dangerous toxics, application of lead based paint and safety on the construction site.
2) Companies profit from the reduction of CO_2; although these measures are already increasingly applied in tenders, the numbers of tenders in which it is applied and the impact is has on the tenders is, in the opinion of the author, not enough. If the reward is, for reducing the environmental impact of a structure is high enough, this system will sustain itself and reduction will be at its highest.

Both possibilities require a well considered framework which determines CO_2 emissions. It is important this framework receives support from all actors in the construction industry. Well considered scopes need to be at the base of this framework.

Types of contracts

A bid-built contract leaves little room for the construction company to reduce CO_2 emissions. Although the client (government) could instruct the engineering firm, making the design, to implement energy and CO_2 reducing measures; it removes the possibilities for construction companies to make improvements in the design.

Contracts which allow construction companies to introduce ideas to reduce CO_2 emissions are favorable. Expected is that no considerable difference in emission will be found between D&B, DBM,DBMO or DBFMO; the literature study showed that most of the emissions are produced during the production and construction of the civil engineering work and not in maintenance. Reimbursing construction companies for innovative CO_2 reducing ideas should be an important requirement in the tender.

11.2.3. Producers of construction materials

Companies producing construction materials should research more efficient ways to produce materials. And replace fossil fuels with CO_2 neutral fuels (like biodiesel and garbage). Cement factories should research the possibilities to intercept the process bound emissions before they come into the air. Concrete factories should focus on replacing CEM I in concrete mixtures and reducing cement in concrete mixtures. Prefab factories should research possibilities to minimize reinforcement in their elements. Switching to green electricity will also reduce CO_2 emission. Considerable reductions can be obtained by reducing the transport distances of raw material.

11.2.4. Construction companies

Construction companies are recommended to apply prefab construction methods rather than insitu construction. Besides the total emissions in prefab construction are lower than insitu construction, the emissions of the company (scope 1 and 2) are lower. From a construction company's point of view the implementation of green electricity and carpooling are valid options because it reduces CO_2 emission in scope 1 and 2.

Costs of prefab elements

The reason insitu construction is often preferred over prefab construction are the costs. Only a few factories in the Netherlands are capable of producing prefab elements which influences the price. For construction companies it is therefore advisable to only use prefab construction if it has a positive influence on the tender.

Insitu construction

Construction companies should research the possibilities to implement weight reduction in insitu decks. Although this is already technically possible the cost are too high to implement it in short spans. The implementation of high strength concrete in insitu concrete structures should result in reductions of the emissions of an insitu concrete structure. However using high strength concrete insitu poses some organisational difficulties. Reductions by implementing weight reduction and HSC insitu is mostly in scope 3 and not in scope 1 and 2.

Shadow price

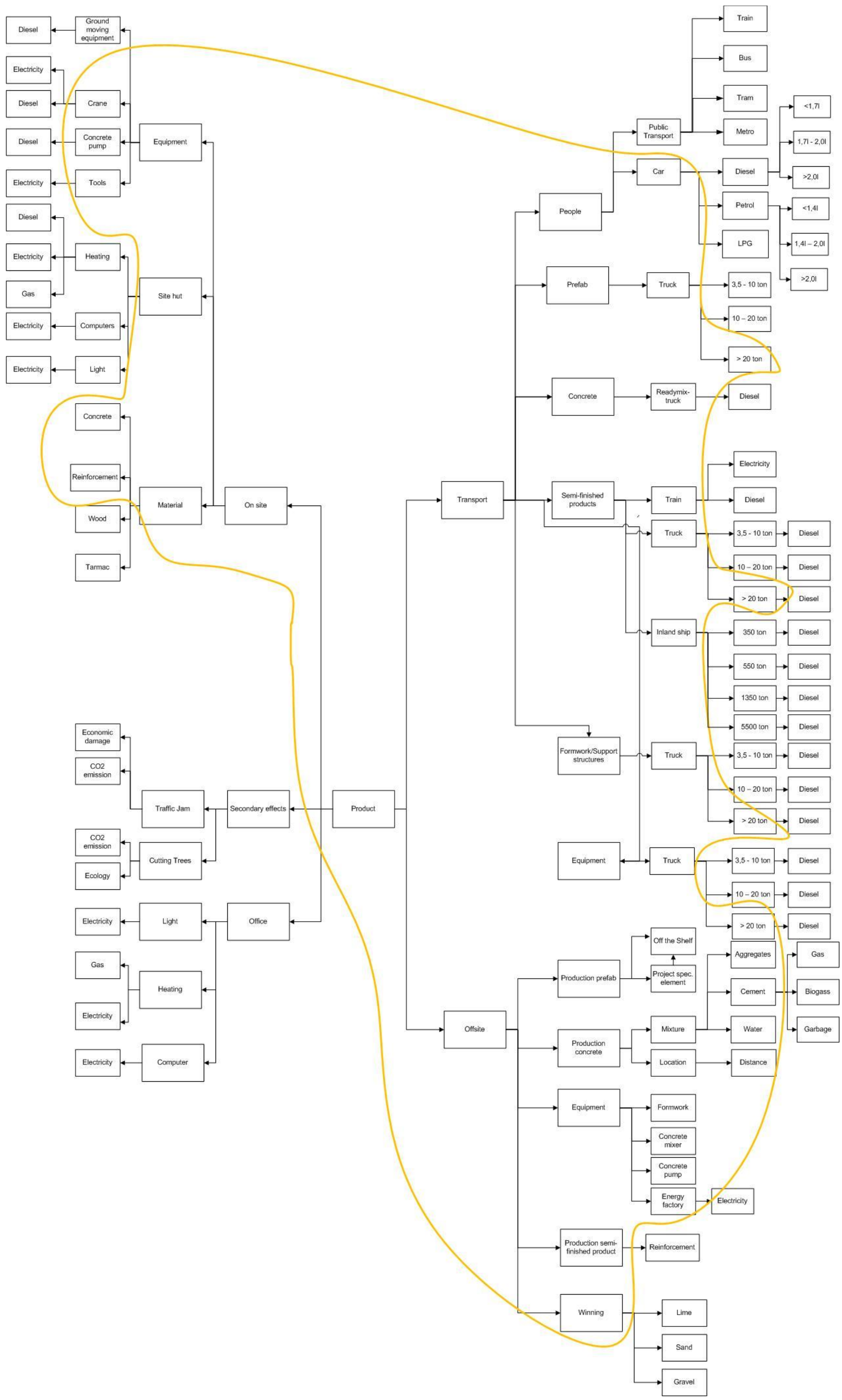
Currently the shadow price of CO_2 is valued on €25,- /ton CO_2. On a project level these cost are small in comparison with the entire project cost. Reimbursing the CO_2 emission could improve the chance of a construction company in a tender.

Informing employees

Awareness among employees of construction companies on CO_2 emissions and emission reducing measures is still limited. If there is an increase in attention to the environmental impact of a structure in a tender, the possibilities of this opportunity would not be exploited to its full potential. The ignorance on the subject would only results in irritation among the employees working on the tender. Construction companies should therefore invest in ideas to reduce the environmental impact of a structure and communicate this to their employees. Construction companies should see changes in tenders as a way to distinguish themselves from other construction companies, and profit from these new set of rules.

APPENDIX

APPENDIX A : SCOPE



APPENDIX B : EMISSION FACTORS OF PRORAIL

Personenvervoer conventionele personenauto				
B	Benzine	2.780		g CO_2 /liter brandstof
	Diesel	3.135		
	LPG	1.860		
C	Benzine	Klasse		g CO_2 /voertuigkm
		< 1,4 ltr	185	
		1,4 – 2,0 ltr	220	
		> 2,0 ltr	305	
		gemiddeld	215	
	Diesel	Klasse		
		< 1,7 ltr	155	
		1,7 – 2,0 ltr	195	
		> 2,0 ltr	265	
		gemiddeld	205	
	LPG	gemiddeld	175	
D	Minibus max. 9 personen	Benzine	255	g CO_2 /voertuigkm
		Diesel	215	
		LPG	200	
E	Brandstoftype niet bekend	210		g CO_2 /voertuigkm

Bron B en D: CE Delft.

Personenvervoer hybride auto			
F	Middenklasse auto (Toyota Prius, Honda Civic IMA)	125	g CO_2 /voertuigkm
	Hogere klasse auto (Lexus GS450h, Lexus RX400h)	225	

<table>
<tr><td colspan="4">Personenvervoer collectief</td></tr>
<tr><td rowspan="8">G</td><td>Touringcar</td><td>45</td><td rowspan="8">g CO_2 /reizigerskm</td></tr>
<tr><td>Streekbus</td><td>95</td></tr>
<tr><td>Stadsbus</td><td>120</td></tr>
<tr><td>Metro / tram</td><td>100</td></tr>
<tr><td>Stoptrein *)</td><td>100</td></tr>
<tr><td>Intercity *)</td><td>55</td></tr>
<tr><td>Stoptrein+Intercity **)</td><td>65</td></tr>
<tr><td>Hoge snelheidstrein</td><td>60</td></tr>
</table>

<table>
<tr><td colspan="5">Vervoer bulk goederen</td></tr>
<tr><td rowspan="10">B</td><td colspan="2">Vrachtauto > 20 ton</td><td>110</td><td rowspan="10">g CO_2 /tonkm</td></tr>
<tr><td colspan="2">Trekker met oplegger</td><td>80</td></tr>
<tr><td rowspan="2">Trein</td><td>elektrisch</td><td>25</td></tr>
<tr><td>diesel</td><td>30</td></tr>
<tr><td rowspan="4">Binnenvaart</td><td>350 ton</td><td>70</td></tr>
<tr><td>550 ton</td><td>70</td></tr>
<tr><td>1350 ton</td><td>60</td></tr>
<tr><td>5500 ton</td><td>30</td></tr>
<tr><td rowspan="2">Zeevaart</td><td>1800 ton</td><td>75</td></tr>
<tr><td>8000 ton</td><td>30</td></tr>
</table>

<table>
<tr><td colspan="5">Vervoer containers / non bulk goederen</td></tr>
<tr><td rowspan="13">B</td><td colspan="2">Bestelauto</td><td>630</td><td rowspan="13">g CO_2 /tonkm</td></tr>
<tr><td rowspan="3">Vrachtauto</td><td>3,5 – 10 ton</td><td>480</td></tr>
<tr><td>10 – 20 ton</td><td>300</td></tr>
<tr><td>> 20 ton</td><td>130</td></tr>
<tr><td colspan="2">Trekker met oplegger</td><td>95</td></tr>
<tr><td rowspan="2">Trein</td><td>elektrisch</td><td>20</td></tr>
<tr><td>diesel</td><td>25</td></tr>
<tr><td rowspan="4">Binnenvaart</td><td>32 TEU</td><td>65</td></tr>
<tr><td>96 TEU</td><td>75</td></tr>
<tr><td>200 TEU</td><td>60</td></tr>
<tr><td>470 TEU</td><td>50</td></tr>
<tr><td rowspan="2">Zeevaart</td><td>150 TEU</td><td>85</td></tr>
<tr><td>580 TEU</td><td>45</td></tr>
</table>

Elektriciteitsverbruik voor andere doeleinden dan vervoer			
A	NRE	650	g CO_2 /kiloWattuur
	RWE Energy Nederland	650	
	Cogas Facilitair	620	
	Nuon	610	
	Eneco Energie Levering	590	
	Essent Retail	525	
	EnerService Maastricht	495	
	Westland EnergieServices	495	
B	Andere leverancier	615	g CO_2 /kiloWattuur

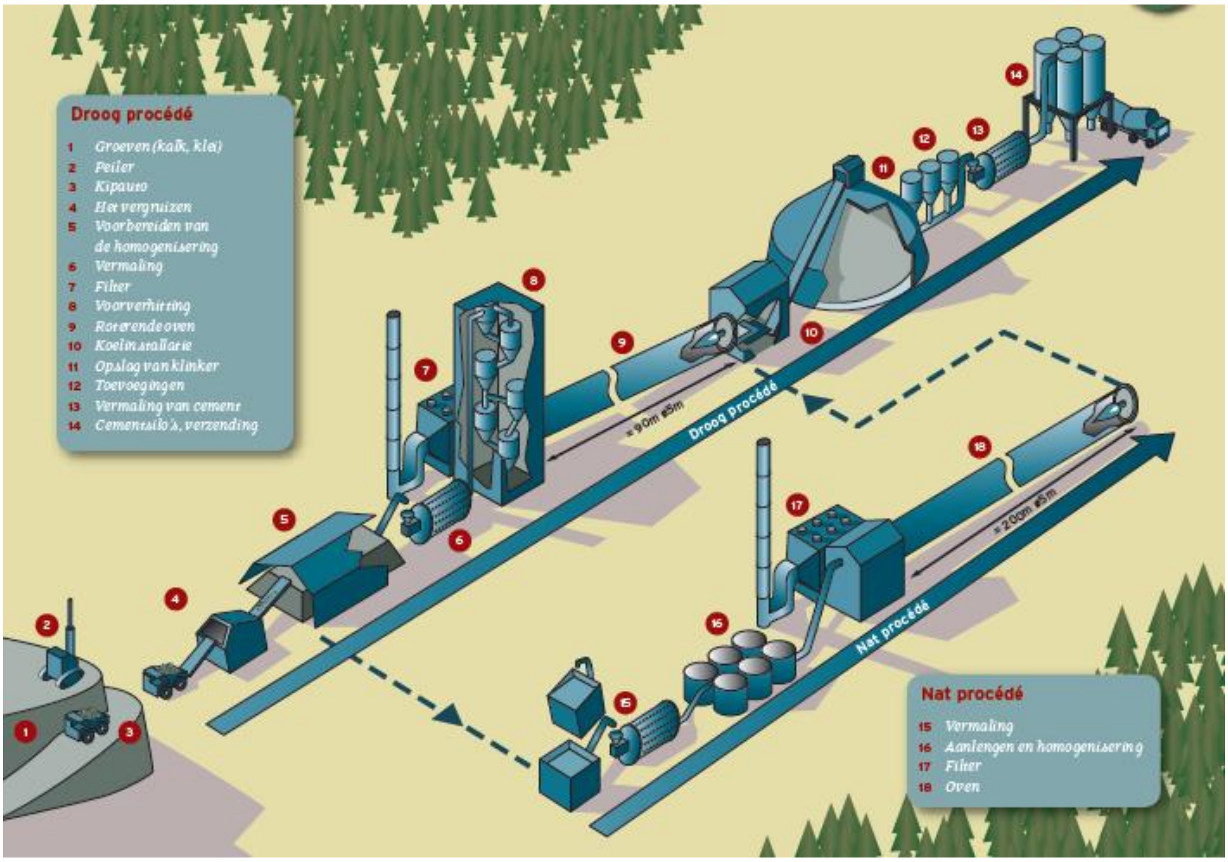
Elektriciteitsverbruik ('groen') voor andere doeleinden dan vervoer				
C[1]	Groene stroom met SMK-Milieukeur	Windkracht	15	g CO_2 /kiloWattuur
		Waterkracht	15	
		Zonne-energie	80	
		Biomassa	zie reken-voorschrift	
D	Groene stroom met SMK-Milieukeur		250	g CO_2 /kiloWattuur
E	Overige groene stroom		300	g CO_2 /kiloWattuur

(ProRail, 2009), (ProRail, 2009)

APPENDIX C : CEMENT

Production of cement

Cement functions as glue that keeps the aggregates together in concrete. The process starts with the winning of lime this is the main substance of cement (65%). The other ingredients of cement are silica (20%), aluminium (10%) and iron oxide (5%). This is put together in the factory and from thereon there are two procedures, the wet and dry procedure. Which procedure is the best depends on the quantity of water in the lime. From there on it goes into the kilns, where the mixture is heated up to 1450°C and after that is cooled to 150°C. After this process the mixture is formed into little pebbles, this is called clinker. During the transformation of lime into clinker ($CaCO_3 \rightarrow CaO + CO_2$) a lot of CO_2 is produced (57% of the whole cement production). Because this CO_2 is process bounded, it cannot be reduced. The clinker is crushed into a homogeneous and fine powder. This is cement. In the following figure the whole process is given.

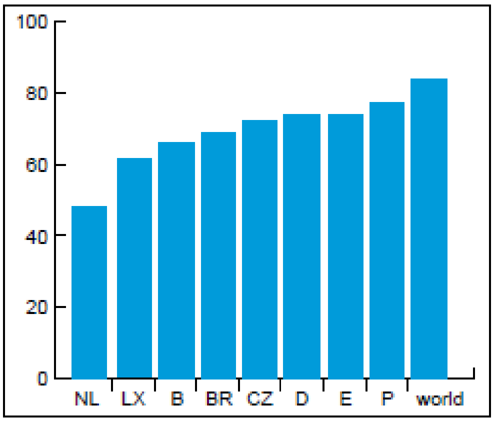


Cement production (FEBELCEM, 2006)

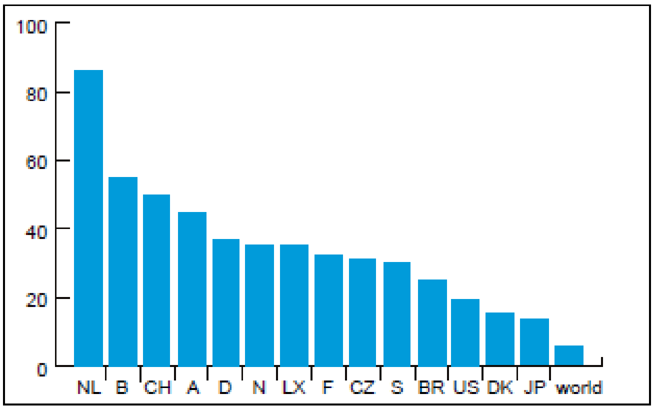
Cement is, due to its high temperatures during production, a big consumer of (fossil) fuels. The cement industry is focussing its attention to reduce emissions. This has resulted in improvements in two fields. The first is the efficiency of the factories. Factories are focussing to use their heat that they produce in the best way possible. Also the input of fossil fuels is reduced as much as possible by replacing them with alternative fuels. Most of the cement factories use (brown) coal, gas or other fuels to power their kiln. ENCI, the biggest producer of cement in the Netherlands is trying to reduce this amount as much as possible. Already a reduction of 85%-90% of reduction of gas is made by replacing it by biomass (ENCI). The Dutch production numbers are used in this research, in other countries these numbers can deviate considerable.

The CO_2 which is formed during the forming of clinker (process bounded emission) is the other focus point of the cement industry. By introducing fly-ash and blast furnace slag the quantity of clinker in cement can be reduced and therefore the CO_2 emission. The most used materials for this are fly-ash and blast furnace slag. These are both industrial by-products. In the Netherlands the quantity of clinker in cement is about 50% and is therefore one of the lowest in the whole world (see figure below). This is because of Dutch regulations and the availability of aggregates (Cement & Beton centrum). Another advantage of introducing fly-ash in cement is that it improves its characteristics.

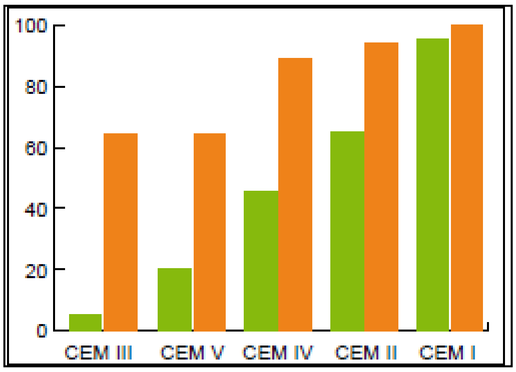
Production facts of cement



Percentage of clinker in cement production (average)



Percentage of alternative fuel in cementproduction (average)



Minimum and maximum clinker level in concrete

(Cement&Beton Centrum)

APPENDIX D : INTERVIEW WITH EMPLOYEE PREFAB FACTORY A

Not for publication

APPENDIX E : DIFFERENCES OF INSITU AND PREFAB CONCRETE STRUCTURES

Transport

Prefab

* Less transport of equipment
* Less travel distance employees
Less people required to produce formwork-->less transport
* Efficiency of transport

Insitu

* Element travels less distance on the road
* Uncertainty with the quantity of concrete--> more transport
* More parties on the construction site --> more transport
More Equipment on site
More construction material

Efficiency Concrete

Prefab

More Recycle/reuse
Possibility to determine strength more precise
Less material due to optimization formwork
Lighter foundation
* More cement in mixture --> fast hardening
* Extra force on element during transport

Insitu

* Old technique--> less likely to improve
Load on structure is fast--> strength overkill
* Uncertainty of the quantity of concrete

Material/Equipment

Prefab

More reuse of formwork
* Less/no transport formwork
* Crane capacity better used
* Crane uses electricity
* Energy consumption factory
* Use of CEM I

Insitu

* More formwork
More equipment
* Longer construction time onsite

* This is also a factor with Project specific concrete

* This is also a factor with "prefab on site"

APPENDIX F : CONCRETE MIXTURES AND ENVIROMENTAL IMPACTS

	C28/C35		C35/C45		C53/C65	
Cement	350	kg/m3	375	kg/m3	390	kg/m3
Sand	800	kg/m3	800	kg/m3	800	kg/m3
Gravel	1050	kg/m3	1050	kg/m3	1050	kg/m3
Water	125	l/m3	125	l/m3	125	l/m3
Additive	1,5	%	0,75	%	0,75	%

Cement mixtures

	C28/C35		CO2 (kg)		Energy (MJ)
Concrete	**Cement (CEM III)**	46%	43,7	27%	229,2
(per ton)	**Reinforcement**	38%	35,7	53%	450,0
	Aggregates	16%	15,0	20%	175,0
		100%	94,3	100%	854,2
	C35/C45		CO2 (kg)		Energy (MJ)
Concrete	**Cement (CEMIII)**	48%	46,8	28%	245,5
(per ton)	**Reinforcement**	37%	35,7	52%	450,0
	Aggregates	15%	15,0	20%	175,0
		100%	97,4	100%	870,5
	C53/C65		CO2 (kg)		Energy (MJ)
Concrete	**Cement (CEM III)**	29%	36,2	19%	189,9
	Cement (CEM I)	30%	37,5	19%	196,4
(per ton)	**Reinforcement**	29%	35,7	44%	450,0
	Aggregates	12%	15,0	17%	175,0
		100%	124,3	100%	1011,3

CO_2 emission and Energy consumption concrete mixtures (van Hattem en Blankevoort, 2010)

	C28/C35				
Concrete	**Cement**	38%	43,7 kg	20%	229,17 MJ
(per ton)	**Reinforcement**	31%	35,65 kg	40%	450 MJ
	Aggregates	13%	14,95 kg	16%	175 MJ
	Formwork	11%	12,65 kg	15%	170,83 MJ
	Transportation	7%	8,05 kg	9%	104,17 MJ
		100%	115 kg	100%	1129,17 MJ

CO_2 emission and energy consumption of concrete

APPENDIX G : DIFFERENT TYPES OF FORMWORK

Insitu construction has a number of constructing methods. Each method has its own characteristics, pros and cons. Below a number of the most commonly used types of formwork is given:

Traditional formwork

This type of formwork mainly consists of a wooden plate, supported with wooden uprights. The formwork is composed on the construction site en is usually only used once.

Wall formwork

This formwork consists of a plate and a support structure of wood, aluminium and/or steel. It is made in the factory and delivered (partially) assembled on the construction site. This type of formwork is very common in the housing industry.

Tunnel formwork

Tunnel formwork is a special kind of formwork where the walls and the floor above are poured in one piece. When the concrete is hardened, the whole formwork is removed and the process starts over again. As the name would suggest this formwork can be used in tunnels but also the housing industry.

Climbing formwork

Climbing formwork is a special type of formwork for vertical concrete structures that rises with the building process. While relatively complicated and costly, it can be an effective solution for buildings that are either very repetitive in form (such as towers or skyscrapers) or that require a seamless wall structure (using gliding formwork, a special type of climbing formwork).

Project formwork

Formwork which is designed for a certain project and can be applied a number of times.

System formwork

System formwork is formwork which is assembled from different elements. These elements are linked with special locks. The formwork plates can be assembled from different elements. System formwork was invented in de 70s. Before that all formwork was built from scratch.

APPENDIX H: DIFFERENT TYPES OF PREFABRICATION

Fixed mould

The fixed mould is a demountable mould which does not need to be opened. After hardening, the element is lifted straight from the mould. To make this possible the mould has some special requirements.

Demountable mould

The mould is composed of a mould bottom and mould sides. The bottom, mostly a steel structure with a plain steel plate, belongs to the permanent equipment of the factory. In this bottom heating and compaction equipment are often built in. This bottom must be plane and horizontally placed. On this mould bottom, the mould sides are placed provided a water tight joint. Before moving the elements the sides must be stripped. The two most common demountable moulds are the table mould and the battery mould.

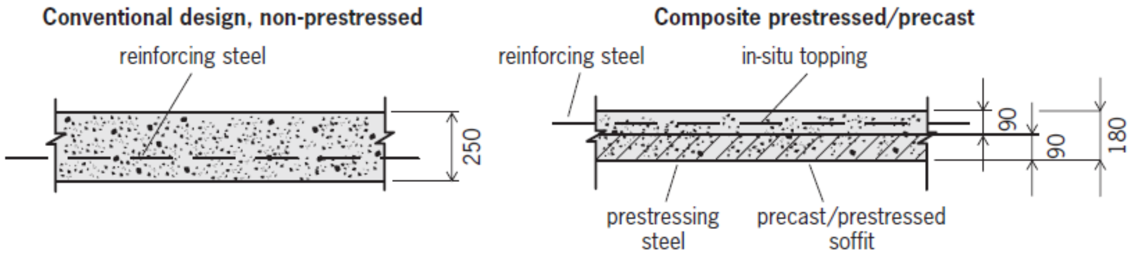
The continuous mould

There are two continues moulds, the extrusion mould technology and the slip forming technology. These techniques are mostly used to produce hollow-core-slabs. The difference between the extrusion mould and the slip form is that the extrusion mould works in one pour and the slip form in multiple pours.

Extrusion mould

Hollow-core-slabs in production (extrusion)

APPENDIX I : REDUCTION IN PREFAB FLOORS AND BEAMS

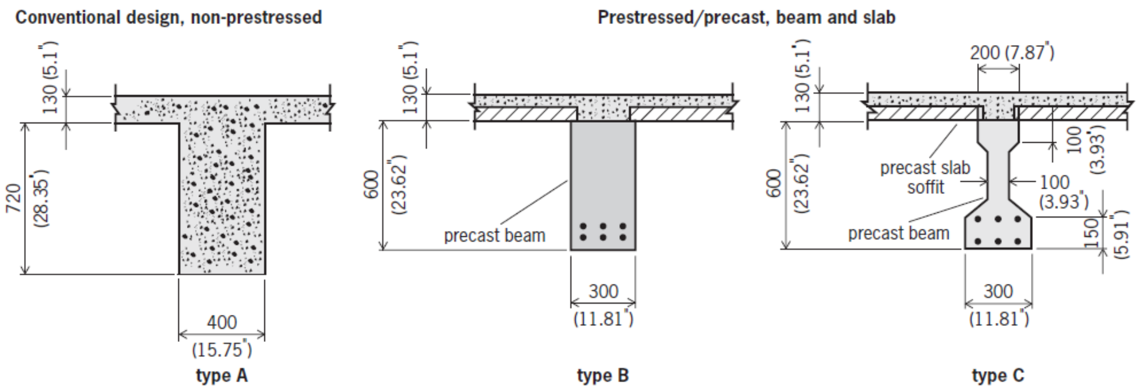


Material	Conventional design, non-prestressed	Prestressed/precast	Material savings
Concrete	0.25 m^3/m^2	0.18 m^3/m^2	28%
Reinforcing steel	18.30 kg/m^2	6.20 kg/m^2	45%
Prestressing steel	—	3.85 kg/m^2	45%

Fig. 1. Flat slabs (one-way span). Design for live load = 4 kPa (83.6 lb/ft²). Clear span = 8 m (26 ft).

Reductions of material in floors

With concrete beams even bigger reductions can be achieved.



Material	Conventional design, non-prestressed Type A	Prestressed/precast Type B	Material savings from type A to type B	Prestressed/precast Type C	Material savings from type B to type C	Material savings from type A to type C
Concrete	0.288 m^3/m	0.18 m^3/m	37.5%	0.113 m^3/m	37.2%	60.8%
Reinforcing steel	42.0 kg/m	6.20 kg/m	66%	6.0 kg/m	—	66%
Prestressing steel	—	8.47 kg/m	66%	8.47 kg/m	—	66%

Fig. 2. Beams. Span = 12 m (39 ft). Clear spacing = 4 m (13 ft) center to center. Live load = 4 kPa (83.6 lb/ft²). Other dimensions are in millimeters (inches).

Reduction of material in beams

(Yee, 2007)

APPENDIX J : CHARACTERISTICS OF A BOX BEAM

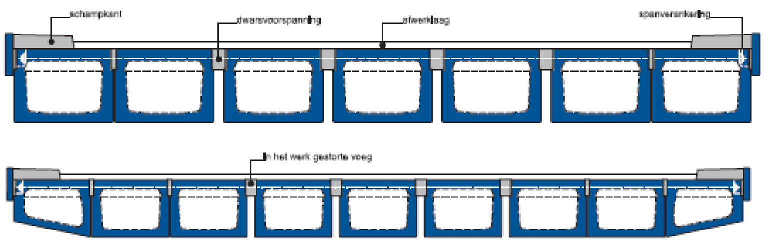
Afmetingen en gewichten

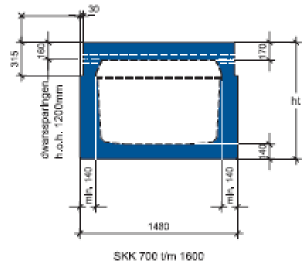
	Afmetingen [mm]	Eigen gewicht [kN/m1]	
	h_t	hol	massief
SKK700	700	16,1	25,4
SKK800	800	17,1	29,1
SKK900	900	17,8	32,8
SKK1000	1000	18,9	36,5
SKK1100	1100	20,3	40,2
SKK1200	1200	21,4	43,9
SKK1300	1300	22,3	47,6
SKK1400	1400	23,2	51,3
SKK1500	1500	24,1	55,0
SKK1600	1600	25,0	58,7

Grootheden prefab ligger

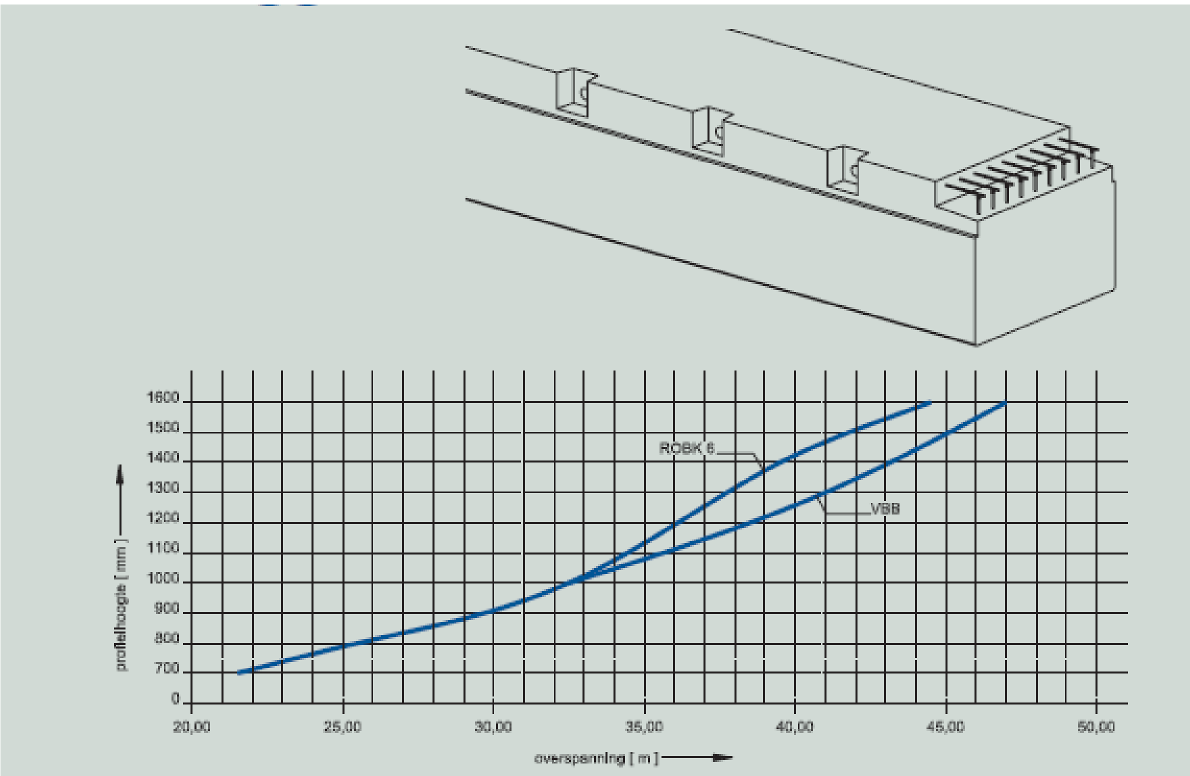
	I_b $*10^9$ [mm^4]	z_b [mm]	A_b $*10^3$ [mm^2]	W_b $*10^6$ [mm^3]	W'_b $*10^6$ [mm^3]	W''_b $*10^6$ [mm^3]
SKK700	39	365	590	106	116	144
SKK800	53	406	624	131	136	169
SKK900	72	457	657	158	163	203
SKK1000	95	508	689	186	192	239
SKK1100	121	558	732	216	223	276
SKK1200	150	608	772	247	254	316
SKK1300	184	658	803	279	287	356
SKK1400	221	709	833	312	320	398
SKK1500	263	758	864	347	355	441
SKK1600	308	810	895	380	391	485

Dwarsdoorsnede SKK-brug





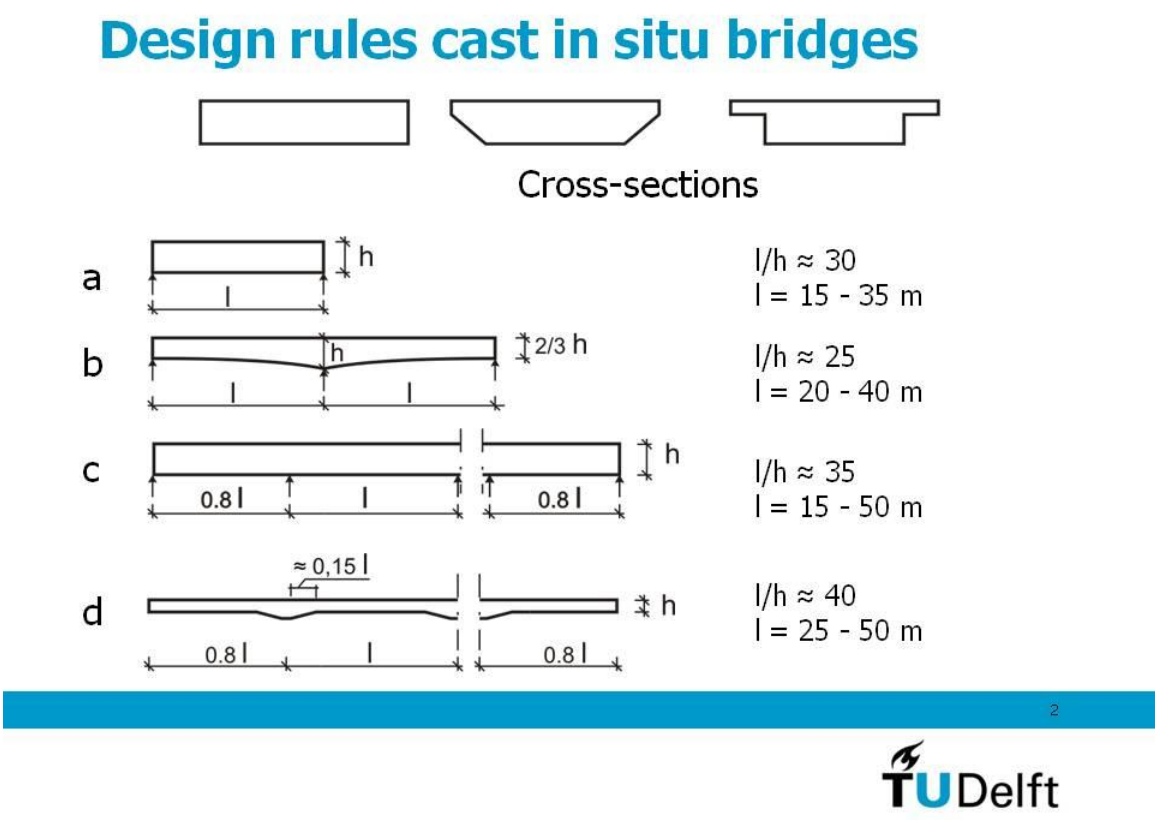
Characteristics and cross section of deck



Span characteristics of a box beam

(Spanbeton)

APPENDIX K : SPANS OF INSITU DECKS



(Civiele Techniek TUDelft)

APPENDIX L : INTERVIEW WITH CALCULATOR HEIJMANS

Not for publication

APPENDIX M: INTERVIEW WITH EMPLOYEE PREFAB FACTORY B

Not for publication

APPENDIX N: TABLES FROM STREAM

Vrachtauto's	GVW	Capaciteit[1]	Beladingsgraad op basis van laadvermogen in tonnen[2]	Productieve km's[3]
	ton	ton	%	%
Bulk				
>20 ton	34	27	66	50
Trekker met oplegger	36	27	73	59
Non-bulk/Container				
<3,5 ton (bestelauto)	3,2	1,5	35	61
3,5-10 ton	6,9	4,0	36	74
10-20 ton	14	10	36	73
>20 ton	34	27	42	67
Trekker met oplegger	36	27	38	87

1 NEA/Sterc/Transcare, 2002.
2 CBS, 2005.
3 Bulk: CBS 2005, Container: CE, 2003.

Energiegebruik en logistieke gegevens voor binnenvaart

Binnenvaart	AVV-klasse	CEMT-klasse	Capaciteit	Beladings-graad	Productieve km's	Energie-gebruik[1]
			ton	% laad-vermogen in tonnen	%	MJ/vkm
Bulk						
Spits	2	I	350 ton	66	78	113
Kempenaar	3	II	550 ton	66	78	178
Rhine Herne Canal Ship	7	IV	1.350 ton	66	78	412
Koppelverband	25	-	5.500 ton	66	78	656
Four barges Convoy set	18	VIb	12.000 ton	66	78	970
			TEU	% bezette container-plaatsen		
Containers						
Neo Kemp	4	-	32 TEU	65	98	149
Rhine Herne Canal Ship	7	IV	96 TEU	65	98	363
Container ship (Rhine)	9	Va	200 TEU	65	98	570
Container ship (JOWI class)	9	-	470 TEU	65	98	1.040

1 Dit energieverbruik geldt alleen onder aanname van de genoemde logistieke parameters. Containers zijn gemiddeld beladen met 10 ton/TEU.

(CE Delft, 2008)

APPENDIX O : PLANNING FROM PREFAB FACTORY C

Not for publication

APPENDIX P : CALCULATION VALUES

Material

For the production of concrete a number of values can be found. There are different values for the CO_2 emission, energy consumption and concrete mixtures. In the quick scan tool (QST) there are standard values taken for mixtures, energy consumption and CO_2 emission. These are consequently used in the tool. In Appendix F concrete mixtures are given with their particular CO_2 emission and energy requirements (van Hattem en Blankevoort, 2010)(Cement & Beton centrum). In the model two mixtures of concrete are used, C35/C45 and C53/C65. These mixtures are applied the most in the construction industry. C35/C45 with insitu and C53/C65 with prefab (see Appendix D, Appendix L, Appendix M). Important is to notice that there is a difference in the cement use between the two mixtures. C35/C45 only uses CEM III, C53/C65 uses both CEM I and CEM III. CEM I is cement which consists of 95% Portland cement, in CEM III fly-ash or other additives are added (up to 95%). Therefore more CO_2 is emitted during the production of CEM I cement than CEM III cement. Because C53/C65 consists of both CEM I and CEM III the emission per m^3 concrete is higher. CEM I consists of 3 times more CO_2 than CEM III.

The standard quantity of reinforcement is 125 kg/m^3 for columns, abutments and foundation. This quantity is the same for both prefab and insitu. For decks there is 50 kg/m^3 prestressed steel and 75 kg/m^3 reinforcement steel in concrete. The quantity of prestressing and reinforcement in beams depend on the difference in load on the structure (see chapter 6).

The values which are used for the calculations of the emission consist of the winning of the (primary) material and making it into a (semi)finished product. The transportation is not included in this, the same goes for production of concrete (elements). This will be discussed in the next paragraphs.

Transport

Emission values of transport are derived from the “CO_2-Prestatieladder” of ProRail. The values from the “CO_2-Prestatieladder” are derived from STREAM (a research of all different kinds of transport) (CE Delft, 2008). This study does not only show the fuel consumption of transportation vehicles, but also energy consumption, average loading and effective kilometres of the most common transport equipment. This provides the perfect platform to make calculations about the quantity of transport of materials. The emission values of ProRail are given in Appendix B. The most important tables of STREAM are given in Appendix N.

The QST will incorporate the direct transport required for the construction of the viaduct. This contains the direct transport of construction material, formwork, and onsite equipment. Also the transport of workers will be incorporated. The shipment of raw material and transportation of construction materials to the construction site is a process difficult to overview from a contractor’s perspective. Often trucks drive empty and ships are not loaded to their maximum capacity. To resolve these uncertainties, the average loading and effective kilometres, derived from STREAM, are incorporated in the calculations.

Factory

Man-hours

The required man-hours in the factory for project specific formwork (Cat IV) are derived from a schedules of a prefab factory (Appendix O). The man-hour requirements for “off the shelf” prefab elements (Cat V) are formulated via estimates based on experience, acquired knowledge and interviews (see Appendix D). The calculation values comprise all the actions required in the factory for producing concrete elements, such as unloading of the truck, placing the formwork, the reinforcement and pouring the concrete.

It is assumed that the production of concrete requires no labour. This has two reasons, the production of concrete is almost fully automated; therefore little labour is required. When the truck arrives there is no physical work required to unload and mix the concrete. The whole process uses conveyor belts. In both situations the energy consumptions and CO_2 production is the same. No big differences will therefore occur during the process.

Energy

The quantity of energy required to operate a concrete mixer is information acquired from Heijmans Landelijke Specialismen, and amounts to 0,16l diesel/m^3 produced concrete. The energy requirements of a factory are obtained from prefab factory B (Appendix M). The values are the total quantities of electricity and gas used over one year. These values are transferred into energy/m^3.

Onsite

Man-hour

The number of man-hour in a project is an important parameter for the calculation of the energy requirements and CO_2 emission of a project. Less man-hour required onsite means less transport of labourers and less emissions onsite. Via a number of interviews with a calculator of Heijmans the number of man-hour in a project is obtained (Appendix L). The number of man-hours will be used to calculate the total amount of crane time. It is important to acknowledge that these values are averages, and the values that are given are for 'standard' projects. Special requirements or difficult structures could lead to other values. The numbers incorporate preparation, construction and after treatment. Only the construction of the load bearing structure is incorporated.

Energy

The energy required onsite is a combination of type and time of equipment required and the emission of the site office (Appendix L). The fuel consumption of equipment is obtained from multiple sources; via Heijmans foundation techniques, Heijmans tension techniques, a calculator of Heijmans, the project carbon calculator (Koninklijke BAM groep NV, 2006) and the scope 3 analysis of KWS (van Hattem en Blankevoort, 2010).

Difference in categories

The quick scan tool distinguishes 5 different construction processes. The next paragraph discusses what the qualitative influence of each construction method is on the build of the structure. The most important assumption is that all the structures must agree to the same functional design. Within this functional design all the measures and volumes can change.

Material

As mentioned in the previous chapter, structures constructed on the construction site (Cat I, Cat II and Cat III) have the same material use. All these structures are constructed with the same type of concrete and the only difference is in the construction method. All these structures are constructed from C35/C45 concrete. The prefab structures (Cat IV and Cat V) are constructed from C53/C65 concrete. This influences the dimensions of the structure. The structural assumptions of the tool are discussed in chapter 6. The deck constructed with Cat IV has the same dimensions as the deck constructed in Cat I, II, and III. The deck constructed from box beams (Cat V) reduces the material usage.

Transport

One of the main differences between prefab and insitu is the quantity of transport. As mentioned before the quantity of material is different between prefab and insitu. Prefab construction requires less equipment onsite.

The transport of concrete however is less efficient with prefab elements because, in general, the transportation distance by ship and truck is longer. Transportation by road is less efficient than transportation by ship.

Another difference is the travel distance of the workers to factory and the construction site. Workers of the factory usually live closer to the factory than workers to the construction site. The distance between winning of the primary materials and the concrete factory/prefab factory, the distance between the concrete factory/prefab factory and the construction site as well as the travel distance between home and the construction site/ prefab factory are variables in the model. The distances of the crane and concrete pump are variables in the model as well.

Factory

The only energy which insitu construction methods require, in the factory, is the production of concrete. With prefab elements (Cat IV and Cat V), this is different. The production of project specific prefab elements (Cat IV) a large number of man-power is required. For the production of prefab elements “off the shelf” (Cat V), there are few man-hours required. The number of man-hours is required to produce a project specific element (Cat IV) is comparable with the numbers found with production of insitu concrete structures. The energy requirements of these elements are different than the emissions onsite. The energy required to heat up and lights the building, is incorporated in the tool.

Elements produced in prefab factories require very little man power

The production of “off the shelf” concrete elements (Cat V) is totally different than the production of elements in the other categories. The production is fully automated. The trade off is that there is less man-power required for the same amount of production therefore the production speed is higher. The formwork in a factory is reused many times and the formwork only needs to be cleaned. After the cleaning, the reinforcement is placed and the concrete is poured. This results in a much larger output of concrete per worked hour. Due to the more efficient production of Cat V elements, the energy requirements per element are assumed the same. Because the formwork of the box beam girders (Cat V) is optimized and weight reduction is built into the formwork the elements are lighter and big material savings are achieved (see Appendix J).

Onsite

Onsite there are considerable differences between prefab and insitu construction methods. The difference in construction method between Cat I and Cat II is only minor. The differences in the construction process are because of the differences in production time of the formwork, the other processes are the same. The construction process (onsite) of Cat IV and Cat V are also similar. The main difference between Cat IV and Cat V is the construction of the deck. Cat IV divides the deck into transportable chunks; the elements will be post-tensioned onsite. A deck from “off the shelf” prefab is constructed from prefab beams and an insitu topping. The number of crane hours is comparable between these construction methods. Cat III, the production of prefab elements onsite, has components of both insitu as well as prefab. The number of man-power that is required is comparable to the production of concrete elements onsite (Cat I and Cat II), the crane actions are comparable with Cat IV or Cat V. Cat III has negative aspects of both construction methods, therefore more crane time is required. Because the working conditions in Cat III are slightly better than for insitu onsite, the speed of construction formwork is slightly higher.

APPENDIX Q : THE QUICK SCAN TOOL

Introduction

The quick scan tool (QST) is designed to acquire insight in the energy requirements and CO_2 emissions in the construction of a viaduct. In this research the quick scan tool will be utilised to get insight in the difference in emission of various construction methods. In tenders it can be used to generate insight in emissions of a specific project. The tool is designed to give a rough estimate of the energy consumption and CO_2 emission of the built of a structure and show the difference between several construction methods. It is important that the input data is easy filled in. This chapter explains the working of the tool and the basic thoughts behind the calculations. In Appendix R screenshots of the model are given, the most important tables and calculation values will also be displayed in the main text.

The in and output

The CO_2 emission of a project depends on a number of variables; those variables are used as input for the tool.

Some basic variables that should be filled in are:

- Quantity of concrete
- Size of elements
- Number of elements
- Distance of primary materials-prefab factory
- Distance of primary materials-concrete factory
- Distance of prefab factory-site
- Distance of concrete factory-site
- Project time
- Type of electricity supplier
- Types of cars driven
- Whether or not there is electricity available on the construction site.

The result is a program which compares different construction methods with each other, and compares them in energy consumption and CO_2 emission. It displays the influence of changes in the construction process. The elementary difference between the QST and other tools, like DuboCalc, is that variants are compared based on construction methods instead of material use. The QST is developed to provide insight in the difference in emissions of construction methods, how this is dived over different contributors, and which measures can be taken to reduce the energy consumption and CO_2 emission.

The next couple of paragraphs discuss the calculations of the model. Screenshots of the model will be displayed in Appendix R. The most important screenshots will also be incorporated in the main text.

The input field (paragraph 7.3)

The input field consists of the design parameters of the project. The most distinguishable values of a project are filled in. The quantities are filled in are the quantities which a viaduct would require if it was constructed, onsite, with C35/C45 concrete. The tool calculates the variations that occur when a different construction method is applied. The input variables are dived in four categories: project values, transport, onsite and electricity. These variables are important because they influence the quantity of material required and emissions due to production, transportation and onsite.

In project values the basic design quantities are filled in. Under heading transport all distances are filled in. The type of car used by the construction company can also be filled in. Under heading onsite the types of cranes used can be filled in, as well as if electricity is available onsite. The last category is electricity. Each energy supplier can be filled in. A distinction is made between electricity onsite, in the concrete factory and prefab factory. The reason these variables are chosen is because these variables change for each project and are different for each contractor.

Project name	**A2 Ringweg Eindhoven KW15**		
Project location	**Eindhoven**		
		Input fields	
	Project values		
	Deck		
	Quantity of concrete (deck)	388,8	m3
	Surface of deck	648,0	m2
	Length of deck	36,0	m
	Column		
	Quantity of concrete (per column)	3,18	m3
	Number of columns	4,0	
	Height of column	5,0	m
	Abutment		
	Quantity of concrete (abutment)	45,0	m3
	Number of abutments	2,0	
	Height of abutment	2,5	m
	Width of abutment	1,0	m
	Foundation		
	Type of piles	Pile foundation (average)	
	Number of piles	60,0	
	Width of pile	0,45	m
	Depth	18,5	m
	Duration project	30,0	weeks
	Transport		
	Primary materials- concrete factory	100,0	km
	Concrete factory- construction site	25,0	km
	Primary materials-prefab factory	100,0	km
	Prefab factory- construction site	25,0	km
	Average travel distance car (to site)	50,0	km
	Average number of people per car	4,0	people
	Average travel distance car (to factory)	25,0	km
	Type of car	Hybrid	
	Distance crane	50,0	km
	Distance concrete pump	50,0	km
	Onsite		
	Electricity available	Yes	
	Crane	Electric	
	Electricity		
	Onsite	Water (with SMK stamp)	
	Concrete factory	Water (with SMK stamp)	
	Prefab factory	Water (with SMK stamp)	

Input field

The output field (paragraph 7.8)

The output field consist of two parts; one numerical part and one graphical part. The numerical part shows the output of all energy and CO_2 required in a project. There is a distinction in five elements. Deck/beam, centre columns, abutment, foundation and standard. Each of these categories is again dived in five elements. Material, transport, factory, onsite and total. The purpose of this numerical part is to show (in absolute values) what the sum of emissions is. All elements are at least expressed in MJ and kg CO_2. Depending on the type of activity, there is also an expression in quantity of electricity or quantity of fuel consumed. To make comparisons between various construction methods, it is possible to compare two variants next to each other. The comparison is only possible in difference in construction methods; it is not possible to define differences in the output field. The second part of the output field shows the results in a graphical way. Multiple graphics are generated in the output field. An overview of the output field is given in Appendix P.

Intermediate calculation sheets (paragraph 7.4)

The calculation sheets process the input variables and combine them with the calculation values to calculate the total energy consumption and CO_2 emission of the total project.

Prefab sheet

The prefab sheet determines the difference in material and loading between constructing the deck of a viaduct with a flat slab deck or a deck constructed with box beams. As stated before, the height of the beam is assumed to be the same height of the deck (chapter 6). The weight of the beam is calculated using the average difference in weight. The weight of the structural topping is also taken into account. The other load on the structure is the loading of the vehicles (4kN/m^2) (NEN 6702)(NEN 6706)(NEN 6723)(Rijkswaterstaat Bouwdienst, 2006). The difference of the load, of the deck, works through on the columns, abutments and foundation.

The beams have a centre to centre distance of 1,5m. Only whole beams are used in the calculation In Appendix J the calculation values of the prefab deck/beam construction is given.

Calculate sheet

The calculate sheet determines the influence of different types of concrete on the size of the structural element. Elements constructed insitu (Cat I, II and III) are constructed with C35/C45 concrete. Prefab elements (Cat IV and Cat V) are constructed in C53/C65. This difference in concrete strength shows in the size of columns and abutments. It is assumed that a reduction of force on the deck (weight and loading) reduces the size of the column and abutments. The implementation of higher strength concrete reduces the size of the columns with (45/65=69%). The size of the foundation is determined by the reduction of weight (incl. the loading) of the total structure. The dimensions of the deck (Cat IV) are not influenced by the implementation of high strength concrete.

Emission and energy factors (paragraph 7.5)

The emission sheets contain the “hard” data acquired from the literature study. These values are combined with the input variables to generate output of emissions and energy.

Electricity sheet

Sheet which contains the emissions of the electricity companies in the Netherlands (ProRail, 2009). These values differentiate from energy suppliers to energy supplier. If an energy supplier changes his production process, these values also change.

Concrete sheet

The concrete sheet shows the energy production and CO_2 emission of concrete per ton. Different types of concrete have different compositions therefore different calculation values. Standard values for reinforcement in concrete are given (van der Wegen, 2008). Important is to acknowledge that different values are available on the production of concrete and reinforcement. Normally, the quantity of reinforcement, just like the mixture of concrete, is determined for each project individually. The values assumed in the tool are averages.

The most important difference between C35/C45 and C53/C65 concrete is the use of CEM I. CEM I (Portland cement) is only applied in C53/C65 concrete, this type of cement contains more CO_2 and has therefore a large influence on the emission of C53/C65 concrete.

Transport sheet

The information in the transport sheet consists of efficiency of trucks, cars and ships. Incorporated in the values are the number of empty rides and average loads of the trucks, the information needed for these calculations are obtained from STREAM and ProRail (CE Delft, 2008) (ProRail, 2009). The energy and CO_2 potential of diesel, petrol and gas are also incorporated in the sheet (Prorail, 2009)(SenterNovem, December 2009). The emission of diesel is also required to calculate emissions of generators, foundation rams, cranes and prestressing equipment.

Equipment sheet

The equipment sheet contains the calculation values about the equipment used onsite. The information is gathered from multiple sources. The information is partly from Heijmans Funderingstechniek and Heijmans Span- en Verplaatsingstechniek and the Project Carbon Calculator (Koninklijke BAM groep NV, 2006). People with experience onsite have provided information on the consumption of fuel of the equipment. The values from ideal production conditions are difficult to use because equipment will not always perform optimal. In the calculation values provided by a calculator of Heijmans (Appendix L), the average production times are incorporated. An average size crane is used. Cranes can run or diesel or electricity (tower cranes). On the construction site (small) diesel cranes are preferred by superintendents because they are more manoeuvrable and therefore more useful on the construction site.

The pile foundation is executed with a power pack. This is not per se the preferred choice of the contractors, but is nowadays the most used, because it is environmental friendly on the construction site. The traditional pile driving frames resulted in a lot of pollution because diesel was spilled during the process. The power pack is less efficient than the traditional pile drive process.

Standard sheet

Each project has basic requirements that need to be available onsite. In the tool this is at least a crane and a site office. To make sure these values are only incorporated once they are stated alone. In, almost, every process a crane is required. A concrete pump, for example, is only needed when concrete needs to be poured. It is too expensive to have such equipment onsite when they are not needed. This sheet contains the transport of the crane and the onsite emissions of a site office.

Calculation values sheets (paragraph 7.6)

Onsite sheet

This sheet divides all the different process onsite and determines how many (man-) hours are required for this process. It is therefore important for the quantity of transport of people as well as the usage of equipment onsite. The information is from a calculator for Heijmans, in Appendix P an overview of the calculation values is given. The values discussed in the interview concern the time required to produce formwork, place reinforcement, pour concrete, install beams etc. The interviews can be read in Appendix L.

Some elements are never produced in a certain manner, especially with the constructions of decks. An insitu deck, for a viaduct, will always be constructed with traditional formwork, and not with system formwork. System formwork is not beneficial for this type of work. A deck will only be constructed with prefab onsite (Cat III) if there is a limited time to install the deck. If for example a road or a rail track need to be closed. If this is the case there will be more equipment and manpower on site to make sure the deck is placed in the set time frame. Because different considerations are important in this way of construction, the comparison with other categories is would become unusable and is therefore neglected. But it is a remark which should be taken into consideration. Decks are most often constructed in Cat I or Cat V. With other elements this is not the case.

Factory sheet

Information about the factory is divided in two sections. The first one is the production of concrete. The information is acquired from Heijmans Landelijke Specialismen. The information is used in every calculation and gives a value for the quantity of energy required to produce concrete.

The second part of the sheet contains calculation values on the time and energy required to produce prefab concrete elements. It is clear that prefab in Cat IV requires more manpower than prefab Cat V. The energy distribution of prefab elements is different between Cat IV and Cat V. Cat IV elements take longer to produce, the equipment required for the production of “off the shelf” prefab (Cat V) uses more electricity, but is more efficient. This results in that the energy requirements for both construction methods are assumed the same. The information is a combination of information acquired from prefab factory A, B, and C (Appendix D, Appendix M, Appendix O)

Overview sheets (paragraph 7.7)

The overview sheets add up all the calculations. All sheets are divided in 5 parts; Material, people, transport, factory and onsite. There are 5 sheets, for each of the categories. The calculations are in essence all the same but, the different calculation values result in different output values. The next couple of sub paragraphs show which calculations are put in these sheets. The 5 overview sheets are called:

- Insitu (Cat I)
- Insitu (Cat II)
- Prefab onsite (Cat IV)
- Prefab (Cat V)

Material

The material part gives an overview of the quantity of material required on the construction site. This is concrete, reinforcement, falsework and formwork.

Deck			
Material	Concrete (reinforced)	972	ton
		846.164	MJ
		94.694	kg CO2
	Scaffolding& Formwork	279	ton

Overview of quantity of materials used and emission

People

Gives an overview of the total number of man-hours required to construct an element. This is a combination of the time required to build the formwork, place the reinforcement, pour the concrete, crane time etc. The total number of man-hour is not used as direct output, but functions as input for other calculations.

People	Formwork	583	mh
	Support	58	mh
	Reinforcement	175	mh
	Pretension	78	mh
	Crane	102	mh
	Concrete pump	97	mh

Number of man-hour required

Transport

The total emission of transport is the sum of transportation of materials, equipment and people. The transport of raw material to the concrete or prefab factory, the transportation of material from the factory to the construction site, the transport of equipment to the site and the transportation of people to the prefab factory and construction site.

Transport	**Material**	972	ton
	(to factory)	100	km
		97.200	Total amount of ton km
		853	l diesel
		33.109	MJ
		2.674	kg Co2
	Material (concrete)	972	ton
	(to site)	25	km
		24.300	Total amount of ton km
		642	l diesel
		24.906	MJ
		2.012	kg Co2
	Equipment		
	Scaffolding&Formwork	279	ton
		25	km
		6.966	Total amount of ton km
		184	l diesel
		7.140	MJ
		577	kg Co2
	Concrete pump	17	ton
		100	km
		1.700	Total amount of ton km
		15	l diesel
		575	MJ
		46	kg Co2
	People	1.094	manhours
		50	km
		3.417	Total amount of km
		210	g CO2/km
		243	l petrol
		8.974	MJ
		718	kg Co2
	Total	1.936	Fuel
		74.704	MJ
		6.027	kg CO2

Sum of transportation

Factory

The emissions of the factory depend on the chosen construction method. With insitu constructions the only emissions are of the production of concrete. The emissions of prefab include also the electricity use for the production of prefab elements. The calculations of the number of working-hours and energy consumption are done in the factory sheet.

Factory	Concrete Factory	972	ton
	(mixing)	671	kWh
		2414	MJ
		409	kg CO2
	Prafab factory	9344	kWh
	(electricity building)	90923	MJ
		9003	kg CO2
	Total	972	ton
		10015	kWh
		93338	MJ
		9412	kg CO2

Energy consumption and CO_2 emission in factory

Onsite

The onsite energy consumption is built up of energy consumer's onsite. These are cranes, prestressing equipment, compacting equipment and concrete pumps. The required man-hours are translated into required equipment time and used in this calculation.

	Crane	102	Hours
		3.313	L diesel
		0	kWh
		128.596	MJ
		10.388	kg CO2
	Pump	8	Hours
		108	L diesel
		4.199	MJ
		311	kg CO2
	Prestressing	16	Hours
		92	L diesel
		1.270	MJ
		288	kg CO2
	Compacting	127	kWh
		0	L diesel
		459	MJ
		78	kg CO2
	Total	3.513	L Diesel
		127	kWh
		134.523	MJ
		11.064	kg CO2

Energy consumer's onsite

APPENDIX R : SCREENSHOTS OF MODEL

Input field

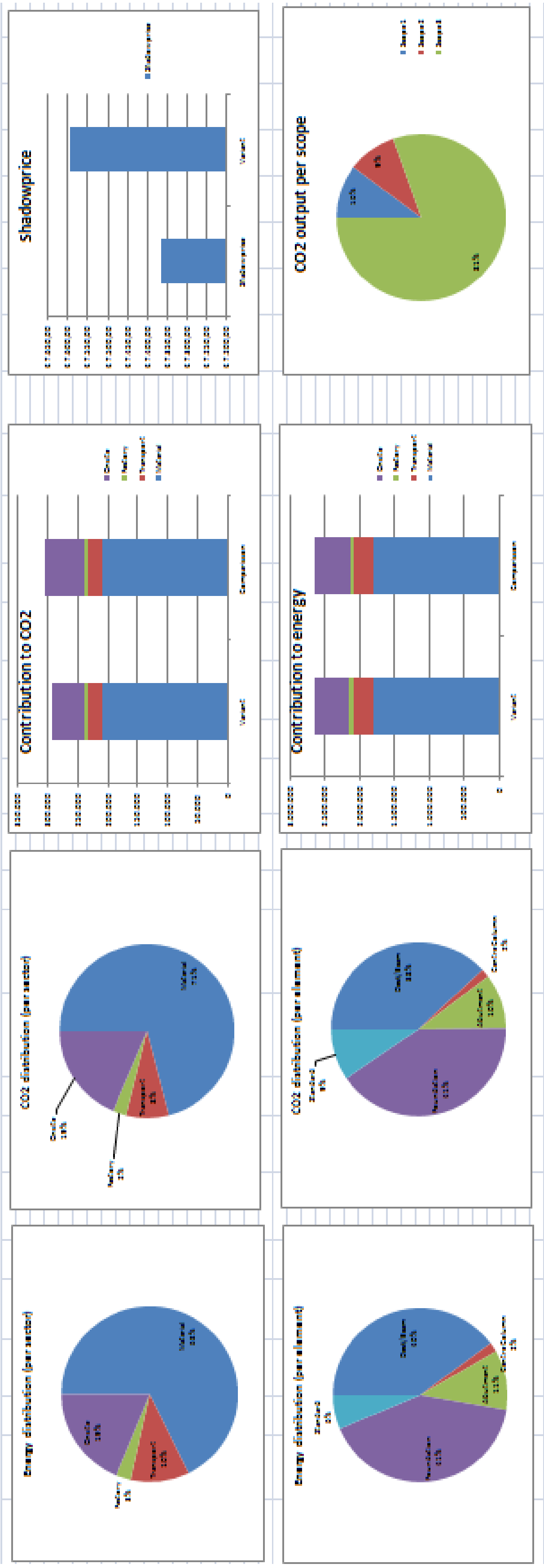
Project name	**A2 Ringweg Eindhoven KW15**		
Project location	**Eindhoven**		
		Input fields	
	Project values		
	Deck		
	Quantity of concrete (deck)	388,8	m3
	Surface of deck	648,0	m2
	Length of deck	36,0	m
	Column		
	Quantity of concrete (per column)	3,18	m3
	Number of columns	4,0	
	Height of column	5,0	m
	Abutment		
	Quantity of concrete (abutment)	45,0	m3
	Number of abutments	2,0	
	Height of abutment	2,5	m
	Width of abutment	1,0	m
	Foundation		
	Type of piles	Pile foundation (average)	
	Number of piles	60,0	
	Width of pile	0,45	m
	Depth	18,5	m
	Duration project	30,0	weeks
	Transport		
	Primary materials- concrete factory	100,0	km
	Concrete factory- construction site	25,0	km
	Primary materials-prefab factory	250,0	km
	Prefab factory- construction site	150,0	km
	Average travel distance car (to site)	50,0	km
	Average number of people per car	2,0	people
	Average travel distance car (to factory)	25,0	km
	Type of car	Average	
	Distance crane	50,0	km
	Distance concrete pump	50,0	km
	Onsite		
	Electricity available	Yes	
	Crane	Diesel	
	Electricity		
	Onsite	NUON	
	Concrete factory	NUON	
	Prefab factory	NUON	

Input field (paragraph 7.3)

Output field

		Deck/Beam			Centre Column			Abutment			Foundation			Standard						
		Insitu (Cat I)	Worst case		Insitu (Cat I	Worst case		Insitu (Cat I)	Worst case		Pile foundation	Pile foundation			Worst case		Variant	Comparisson		Percentage
Material	Weight	972	972	ton	32	32	ton	225	225	ton	720	720	ton							
	Total Energy	846.164	846.164	MJ	27.683	27.683	MJ	195.871	195.871	MJ	728.147	728.147	MJ				1.797.866	1.797.866	MJ	100,0%
	Total CO2	94.694	94.694	kg CO2	3.098	3.098	kg CO2	21.920	21.920	kg CO2	89.471	89.471	kg CO2				209.183	209.183	kg CO2	100,0%
Transport																				
	Total Fuel	1.936	1.936	l	102	102	l	514	514	l	4.620	4.620	l	52	52	l	7.224	7.224	l	100,0%
	Total Energy	74.704	74.704	MJ	3.884	3.884	MJ	19.697	19.697	MJ	178.997	178.997	MJ	6.150	6.150	MJ	283.433	277.283	MJ	102,2%
	Total CO2	6.027	6.027	kg CO2	313	313	kg CO2	1.587	1.587	kg CO2	14.454	14.454	kg CO2	660	660	kg CO2	23.041	23.041	kg CO2	100,0%
Factory																				
	Total Electricity	671	671	kWh	22	22	kWh	155	155	kWh	7.418	7.418	kWh				8.266	8.266	kWh	100,0%
	Total Energy	2.414	2.414	MJ	79	79	MJ	559	559	MJ	69.139	69.139	MJ				72.191	72.191	MJ	100,0%
	Total CO2	409	436	kg CO2	13	14	kg CO2	95	101	kg CO2	6.972	6.972	kg CO2				7.489	7.523	kg CO2	99,5%
Onsite																				
	Total Fuel	3.513	3.547	l	380	381	l	2.018	2.025	l	2.813	2.813	l				8.724	8.766	l	99,5%
	Total Electricity	127	0	kWh	4	4	kWh	30	30	kWh	0	0	kWh	45.000	45.000	kWh	45.161	45.034	kWh	100,3%
	Total Energy	134.523	137.640	MJ	14.767	14.794	MJ	78.411	78.602	MJ	109.153	109.153	MJ	162.000	162.000	MJ	498.854	502.189	MJ	99,3%
	Total CO2	11.064	11.118	kg CO2	1.176	1.177	kg CO2	6.337	6.343	kg CO2	8.817	8.817	kg CO2	27.450	36.680	kg CO2	54.844	64.135	kg CO2	85,5%
Total																	Total			
	Total Fuel	5.450	5.483	l	482	483	l	2.531	2.539	l	7.433	7.433	l	52	52	l	15.948	15.990	l	99,7%
	Total Electricity	798	671	kWh	26	26	kWh	185	185	kWh	7.418	7.418	kWh	45.000	45.000	kWh	53.427	53.300	kWh	100,2%
	Total Energy	1.057.806	1.060.923	MJ	46.413	46.441	MJ	294.538	294.729	MJ	1.085.436	1.085.436	MJ	168.150	168.150	MJ	2.652.343	2.655.679	MJ	99,9% S
	Total CO2	112.194	112.275	kg CO2	4.600	4.602	kg CO2	29.938	29.951	kg CO2	119.714	119.714	kg CO2	28.110	37.340	kg CO2	294.557	303.881	kg CO2	96,9%
CO2 per scope	Scope 1	12.281		kg CO2	1.287		kg CO2	6.775		kg CO2	9.126		kg CO2	660		kg CO2	30.128		kg CO2	
	Scope 2	78		kg CO2	3		kg CO2	18		kg CO2	0		kg CO2	27.450		kg CO2	27.548		kg CO2	
	Scope 3	99.836		kg CO2	3.311		kg CO2	23.146		kg CO2	110.588		kg CO2	0		kg CO2	236.881		kg CO2	

Output field (numerical) (paragraph 7.8)



Output (graphical) (paragraph 7.8)

Emission and energy factors

Grey electricity		g CO2/kWh
	NRE	650
	RWE Energie Nederland	650
	Cogas Facilitair	620
	NUON	610
	Eneco Energie leverancies	590
	Essent Retail	525
	EnerService Maastricht	495
	Westland Energie Services	495
	Other	615
Green electricity	Wind (with SMK stamp)	15
	Water (with SMK stamp)	15
	Sun(with SMK stamp)	80
	Green electricity (with SMK stamp)	250
	Green electricity (without SMK stamp)	300
Note: 1 kWh = 3,6 MJ		
	Electricity onsite	610
	Electricity concrete factory	610
	Electricity prefab factory	610
Source: ProRail		

Electricity (Emission and energy factors/ paragraph 7.5)

	C28/C35				
Concrete	**Cement**	38%	43,7 kg	20%	229,17 MJ
(per ton)	**Reinforcement**	31%	35,65 kg	40%	450 MJ
	Aggregates	13%	14,95 kg	16%	175 MJ
	Formwork	11%	12,65 kg	15%	170,83 MJ
	Transportation	7%	8,05 kg	9%	104,17 MJ
		100%	115 kg	100%	1129,17 MJ
	Type of concrete	C35/45	45	n/mm2	100,00%
		C53/65	65	n/mm2	69,23%
	Weight Concrete	2,5	ton/m3		
	(reinforced)	25	kn/m3		
	Reinforcement	0,125	ton/m3		
		0,050	ton/ton	column abutment	
	prestressing	0,05	ton/m3		
		0,02	ton/ton		

						kg/m3	kg/ton
	C28/C35		CO2 (kg)		Energy (MJ)		
Concrete	**Cement (CEM III)**	46%	43,7	27%	229,2	350	140
(per ton)	**Reinforcement**	38%	35,7	53%	450,0	125	50
	Aggregates	16%	15,0	20%	175,0	1850	740
		100%	94,3	100%	854,2		
	C35/C45		CO2 (kg)		Energy (MJ)		
Concrete	**Cement (CEMIII)**	48%	46,8	28%	245,5	375	150
(per ton)	**Reinforcement**	37%	35,7	52%	450,0	125	50
	Aggregates	15%	15,0	20%	175,0	1850	740
		100%	97,4	100%	870,5		
	C53/C65		CO2 (kg)		Energy (MJ)		
Concrete	**Cement (CEM III)**	29%	36,2	19%	189,9	290	116
	Cement (CEM I)	30%	37,5	19%	196,4	100	40
(per ton)	**Reinforcement**	29%	35,7	44%	450,0	125	50
	Aggregates	12%	15,0	17%	175,0	1850	740
		100%	124,3	100%	1011,3		

Overview of Sources:
Source: Cement&Beton centrum
Source: Scope 3 analysis KWS
Source: DuboCalc
Source: Van der wegen
Source: Ton van der Hunen (Heijmans)

Concrete (Emission and energy factors/ paragraph 7.5)

			MJ/l	g Co2/l						
Emissionfactor	Diesel		38,8	3135,0						
	Petrol		35,2	2780,0						
	Average		37,0	2957,5						
			Source: Senterni	Source: ProRail						
			MJ/m3	gCo2/m3						
	Natural Gas		31,7	1825,0						
Efficiency	**Class**	**Weight (t**	**Occupancy**	**Effective km**	**Average cargo**	**Energy (MJ/**	**Energy (MJ/to**	**l/ton km (effec**	**l/ ton km**	**g CO2/ton km**
Inland shipping	350 ton	350,0	66,0%	78,0%	180,2	113,0	0,6	0,0	0,0	70,0
	550 ton	550,0	66,0%	78,0%	283,1	178,0	0,6	0,0	0,0	70,0
	1350 ton	1350,0	66,0%	78,0%	695,0	412,0	0,6	0,0	0,0	60,0
	5500 ton	5500,0	66,0%	78,0%	2831,4	656,0	0,2	0,0	0,0	30,0
	Average	1937,5	66,0%	78,0%	997,4	339,8	0,3	0,0	0,0	57,5
	Source: STREAM, CE Delft									Source: ProRail
Trucks		**Weight (t**	**Occupancy**	**Effective km**	**Average cargo**	**Energy (MJ/**	**Energy (MJ/to**	**l/ton km (effec**	**l/ ton km**	**g CO2/ton km**
bulk	>20 ton	34,0	66,0%	50,0%	11,2	11,5	1,0	0,0	0,0	110,0
non bulk	3-5 ton	6,9	36,0%	74,0%	1,8	5,7	3,1	0,1	0,0	480,0
	10-20 ton	14,0	36,0%	73,0%	3,7	8,8	2,4	0,1	0,0	300,0
	>20 ton	34,0	42,0%	67,0%	9,6	11,2	1,2	0,0	0,0	130,0
	Average	18,3	38,0%	71,3%	5,0	8,6	2,2	0,1	0,0	255,0
	Source: STREAM, CE Delft									Source: ProRail
							Energy (MJ/km)	l/km		**g CO2/km**
Cars	Average		100,0%	100,0%			2,6	0,1		210,0
	Hybrid		100,0%	100,0%			1,6	0,0		125,0
	Luxury		100,0%	100,0%			2,8	0,1		225,0
										Source: ProRail
Truck mixer	10	m3								
	28	ton								
Transport										
	Worker-Site	50								
	Worker-Factor	30								
	Water									
	Road									
Overview of sources										
Source: Senternovem										
Source: ProRail										
Source: STREAM, CE Delft										

Transport (Emission and energy factors/ paragraph 7.5)

		Diesel		
Equipment	**Crane (100t)**	32,5	l/u	
		350,0	kWh	
	Source: BAM Project carbon Calculator	1.260,0	MJ	
	Towercrane	Electric		
		87,0	kWh	
		313,2	MJ	
	Source: BAM Project carbon Calculator			
	Concrete Pump (average)	50,0	m3/uur	
		13,9	l/u	
		150,0	kWh/hour	
		540,0	MJ/(hour)	
	Source: BAM Project carbon Calculator	40,0	kgCO2/hour	
	Formwork	0,1	ton/m2	
	Prestressing (avergae)	10,0	ton/day	
		1,3	ton/hour	
		63,0	Amp (max)	
		380,0	Volt	
		22,7	kWh	(80% power)
		81,6	MJ	
		5,9	l/u	
	Source: Heijmans tension techniques			
	Generator	0,3	l/kWh	
	Source: Dutry Power			
	Compancting concrete	0,1	kWh/ton	
		0,2	kg C02/m3	
		0,1	kg CO2/ton	
	Source: Scope 3 analysis KWS			
	Overview of sources:			
	Source: BAM Project carbon Calculator			
	Source: Heijmans tension techniques			
	Source: Dutry Power			
	Source: Scope 3 analysis KWS			

Equipment (Emission and energy factors/ paragraph 7.5)

Project independ emissions				
Crane (transport)	60,0	ton		
Source: ProRail	100,0	km		
	6.000,0	Total amount of ton km		
	52,3	l diesel		
	6.149,7	MJ		
	660,0	kg Co2		
Site office	15,0	kWh/m2/week		
	25,0	m2		
	10.928,5	kWh	11.250,0	kWh
	39.342,5	MJ		
	2.841,4	Diesel l (from generator)		
	6.666,4	kg CO2	6.862,5	kg CO2
	Source: BAM CO2 Desk			
	Overview of Sources:			
	Source: BAM CO2 Desk			
	Source: ProRail			

Standard (Emission and energy factors/ paragraph 7.5)

		Cat 2			**Cat 3**			**Cat 4**			**Cat 5**		
		Deck			**Deck**			**Deck**			**Deck**		
0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0	mh/m2	Fromwork	0	mh/m2
0,0	mh/m2	Formwork (ver	0,0	mh/m2	Formwork (vert	0,0	mh/m2			mh/m2			mh/m2
0,0	mh/m3	Support	0,0	mh/m2	Support	0,0	mh/m2	Support	0	mh/m2	Support	0	mh/m2
0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0	mh/ton	Reinforcement	0	mh/ton
0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0	mh/m3	Concrete	0	mh/m3
0,0	mh/ton	Prestressing	0,0	mh/ton	Prestressing	0,0	mh/ton	Prestressing		mh/ton			mh/ton
0,0	mh/mh	Crane	0,0	mh/mh	Crane	0,0	mh/deck	Crane	0	mh/element	Crane	2	mh/element
		Beam			**Beam**			**Beam**			**Beam**		
0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0	mh/m2	Fromwork	0	mh/m2
0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0,0	mh/m2	Reinforcement	0	mh/ton	Reinforcement	0	mh/ton
0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0	mh/m3	Concrete	0	mh/m3
0,0	mh/mh	Crane	0,0	mh/mh	Crane		mh/mh	Crane	0	mh/element	Crane	0	mh/element
		Centre Column			**Centre Column**			**Centre Column**			**Centre Column**		
0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0	mh/m2	Fromwork	0	mh/m2
0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0	mh/ton	Reinforcement	0	mh/ton
0,0	mh/m	Concrete	0,0	mh/m	Concrete	0,0	mh/m	Concrete	0	mh/m	Concrete	0	mh/m
0,0	mh/mh	Crane	0,0	mh/mh	Crane	0,0	mh/element	Crane	0	mh/element	Crane	0	mh/element
		Abutment			**Abutment**			**Abutment**			**Abutment**		
0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0,0	mh/m2	Fromwork	0	mh/m2	Fromwork	0	mh/m2
0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0,0	mh/ton	Reinforcement	0	mh/ton	Reinforcement	0	mh/ton
0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0,0	mh/m3	Concrete	0	mh/m3	Concrete	0	mh/m3
0,0	mh/mh	Crane	0,0	mh/mh	Crane	0,0	mh/mh	Crane	0	mh/element	Crane	0	mh/element
		Foundation			**Foundation**			**Foundation**			**Foundation**		
0,0	mh/pile	Pile	0,0	mh/pile	Pile	0,0	mh/pile	Pile	0	mh/pile	Pile	0	mh/pile
0,13	ton/m2												

Concrete factory	0,0	l/m3
	0,0	MJ/m3
	0,0	kWh/m3
	0,0	kg CO2/m3

Source: Heijmans National Specialisms

Cat 4

Deck		
formwork (hor)	0,0	mh/m2
Formwork(vert)	0,0	mh/m2
Support	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Prestressing	0,0	mh/ton
Beam		
Formwork	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Crane	0,0	mh
Centre Column		
Formwork	0,0	mh/column
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m
Crane	0,0	mh
Abutment		
Formwork(hor)	0,0	mh/m2
Forkwork (vert)	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Foundation		
Pile	0,0	mh/pile
Total Formwork		
Abutment (hor)	0,0	mh
Abutment (vert)	0,0	mh
Preperation	22,6	mh
Deck		
Abutment (hor)	0,0	mh
Abutment (vert)	0,0	mh

Cat 5

Deck		
Formwork	0,0	mh/m2
Support	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Beam		
Formwork	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Crane	0,0	mh/bean
Centre Column		
Formwork	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Crane	0,0	mh
Abutment		
Formwork	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3
Foundation		
Formwork	0,0	mh/m2
Reinforcement	0,0	mh/ton
Concrete	0,0	mh/m3

Factory (Part I) Onsite (Calculation values/ paragraph 7.6)

Energy Factory				
Production	0,0	m3/y		
Gas	0,0	m3 gas		
Electricity(incl concrete factory)	0,0	kWh		
Electricity (excl concrete factory)	0,0	kWh		
Electricity per m3	#DEEL/0!	kWh		
Gas per m3	#DEEL/0!	m3		
Energy/m3	#DEEL/0!	MJ/m3		
CO2/m3	#DEEL/0!	kg Co2/m3	#DEEL/0!	kg Co2/m3 (worst case)
Source: Prefab factory B				

Factory (Part II) Onsite (Calculation values/ paragraph 7.6)

Intermediate Computation								
Forces on structure				Weight reduction in prefab beams				
Deck								
Coating	0,1	m		Height [mm]	Hollow	Full		
				700	16,1	25,4	63,4%	
Beam	1,5	m	width	800	17,1	29,1	58,8%	
				900	17,8	32,8	54,3%	
number	12,0			1000	18,9	36,5	51,8%	
	12,0			1100	20,3	40,2	50,5%	
				1200	21,4	43,9	48,7%	
	BGT	**UGT**		1300	22,3	47,6	46,8%	
Flat Bed	15,0	18,0	kn/m2	1400	23,2	51,3	45,2%	
Beam	10,1	12,1	kn/m2	1500	24,1	55,0	43,8%	
Load	4,0	6,0	kn/m2	1600	25,0	58,7	42,6%	
Total	14,1	18,1	kn/m2					
Total Flatbed	19,0	24,0	kn/m2				50,6%	Average weight reduction
		0,8						
Overview of Sources:								
Source: Spanbeton, Boxbeam								
Source: NEN 6702								
Source: NEN 6706								
Source: NEN 6723								
Soruce: ROBK-6								

Prefab (Intermediate calculations/ paragraph 7.4)

Intermediate Computations

	Standaard (ton)	Cat I	Cat I (tot)	Cat II	Cat II (tot)	Cat III	Cat III (tot)	Cat IV	Cat IV (tot)	Cat V	Cat V (tot)
Deck	972,0	100,0%	972,0	100,0%	972,0	100,0%	972,0	100,0%	972,0	75,4%	733,3
Column	31,8	100,0%	31,8	100,0%	31,8	100,0%	31,8	69,2%	22,0	69,2%	22,0
Abutment	225,0	100,0%	225,0	100,0%	225,0	100,0%	225,0	69,2%	155,8	69,2%	155,8
Foundation	720,0	100,0%	720,0	100,0%	720,0	100,0%	720,0	100,0%	720,0	100,0%	720,0
Column	1,0		Column	1,00							
Abutment	1,0		Abutment	1,00							
Weight Deck	972,0		Weight Deck	972,00							
Foundation	1,0		Foundation	1,00							
Type of concrete		C35/45	45	n/mm2	100,0%						
		C53/65	65	n/mm2	69,2%						
Deck cat V		75,44%									
Foundation (case 1)		100,0%		Foundation (comparison)			100,0%				
Foundation piles		100,0		Foundation piles			100,0				
Rounded up		100,0		Rounded up			100,0				
Weight pole		7,2		Weight pole			7,2				

Calculate (Intermediate calculations/ paragraph 7.4)

Deck				Centre Column				Abutment			
Material	Concrete (reinforced)	972	ton	**Material**	Concrete (reinforced)	32	ton	**Material**	Concrete (reinforced)	225	ton
		846.164	MJ			27.683	MJ			195.871	MJ
		94.694	kg CO2			3.098	kg CO2			21.920	kg CO2
	Scaffolding& Formwork	279	ton		Scaffolding& Formwork	8	ton		Scaffolding& Formwork	29	ton
People	Formwork	583	mh	**People**	Formwork	64	mh	**People**	Formwork	401	mh
	Support	58	mh		Support	0	mh		Support	0	mh
	Reinforcement	175	mh		Reinforcement	13	mh		Reinforcement	90	mh
	Pretension	78	mh								
	Crane	102	mh		Crane	10	mh		Crane	61	mh
	Concrete pump	97	mh		Concrete pump	60	uur		Concrete pump	50	uur
Transport	**Material**	972	ton	**Transport**	**Material**	32	ton	**Transport**	**Material**	225	ton
	(to factory)	100	km		(to factory)	100	km		(to factory)	100	km
		97.200	Total amount of ton km			3.180	Total amount of ton km			22.500	Total amount of ton km
		853	l diesel			28	l diesel			197	l diesel
		33.109	MJ			1.083	MJ			7.664	MJ
		2.674	kg Co2			87	kg Co2			619	kg Co2
	Material (concrete)	972	ton		**Material (concrete)**	32	ton		**Material (concrete)**	225	ton
	(to site)	25	km		(to site)	25	km		(to site)	25	km
		24.300	Total amount of ton km			795	Total amount of ton km			5.625	Total amount of ton km
		642	l diesel			21	l diesel			149	l diesel
		24.906	MJ			815	MJ			5.765	MJ
		2.012	kg Co2			66	kg Co2			466	kg Co2
	Equipment				**Equipment**				**Equipment**		
	Scaffolding&Formwork	279	ton		Scaffolding&Formwork	8	ton		Scaffolding&Formwork	29	ton
		25	km			25	km			25	km
		6.966	Total amount of ton km			207	Total amount of ton km			735	Total amount of ton km
		184	l diesel			5	l diesel			19	l diesel
		7.140	MJ			213	MJ			753	MJ
		577	kg Co2			17	kg Co2			61	kg Co2

Overview add-up sheet (part I) (Overview sheets/ paragraph 7.7)

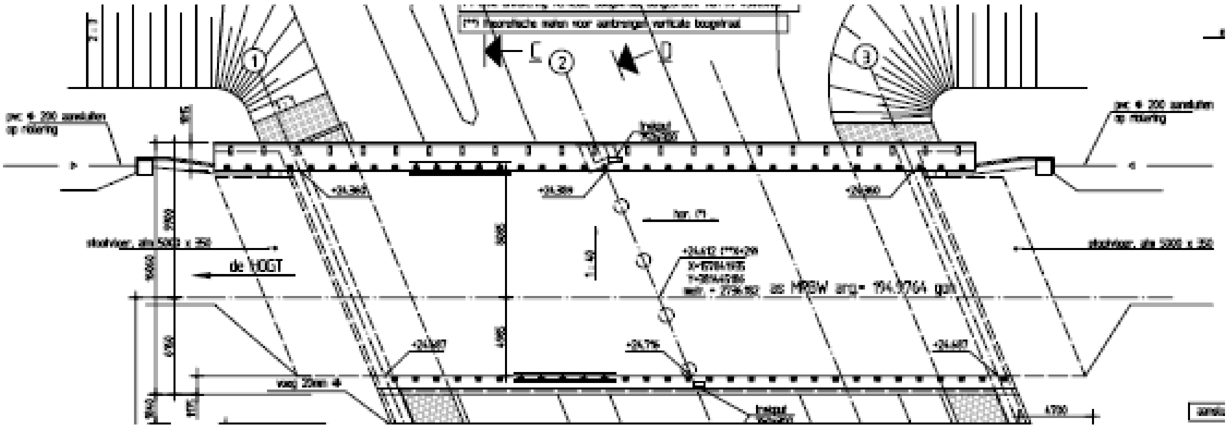
Deck				Centre Column				Abutment			
		718	kg Co2			96	kg Co2			395	kg Co2
	Total	1.936	Fuel		**Total**	102	Fuel		**Total**	514	Fuel
		74.704	MJ			3.884	MJ			19.697	MJ
		6.027	kg CO2			313	kg CO2			1.587	kg CO2
Factory	**Concrete Factory**	972	ton	Factory	**Concrete Factory**	32	ton	Factory	**Concrete Factory**	225	ton
		671	kWh			22	kWh			155	kWh
		2.414	MJ			79	MJ			559	MJ
		409	kg CO2			13	kg CO2			95	kg CO2
Onsite				Onsite				Onsite			
	Crane	102	Hours		**Crane**	10	Hours		**Crane**	61	Hours
		3.313	L diesel			311	L diesel			1.993	L diesel
		0	kWh			0	kWh			0	kWh
		128.596	MJ			12.052	MJ			77.333	MJ
		10.388	kg CO2			974	kg CO2			6.247	kg CO2
	Pump	8	Hours		**Pump**	5	Hours		**Pump**	2	Hours
		108	L diesel			70	L diesel			25	L diesel
		4.199	MJ			2.700	MJ			972	MJ
		311	kg CO2			200	kg CO2			72	kg CO2
	Prestressing	16	Hours								
		92	L diesel								
		1.270	MJ								
		288	kg CO2								
	Compacting	127	kWh		**Compacting**	4	kWh		**Compacting**	30	kWh
		0	L diesel			0	L diesel			0	L diesel
		459	MJ			15	MJ			106	MJ
		78	kg CO2			3	kg CO2			18	kg CO2
	Total	3.513	L Diesel		**Total**	380	L Diesel		**Total**	2.018	L Diesel
		127	kWh			4	kWh			30	kWh
		134.523	MJ			14.767	MJ			78.411	MJ
		11.064	kg CO2			1.176	kg CO2			6.337	kg CO2

Overview add-up-sheet (part II) (Overview sheets/ paragraph 7.7)

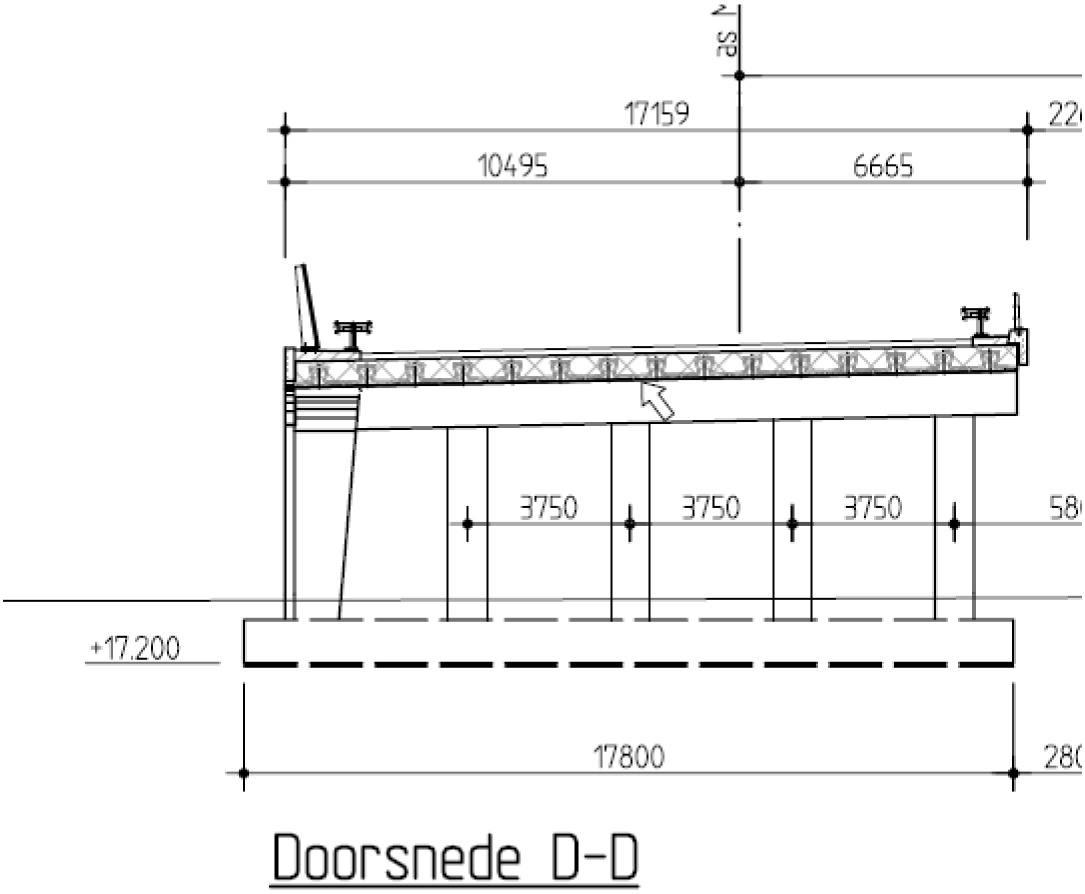
APPENDIX S : INTERVIEW WITH WORK PLANNER OF HEIJMANS

Not for publication

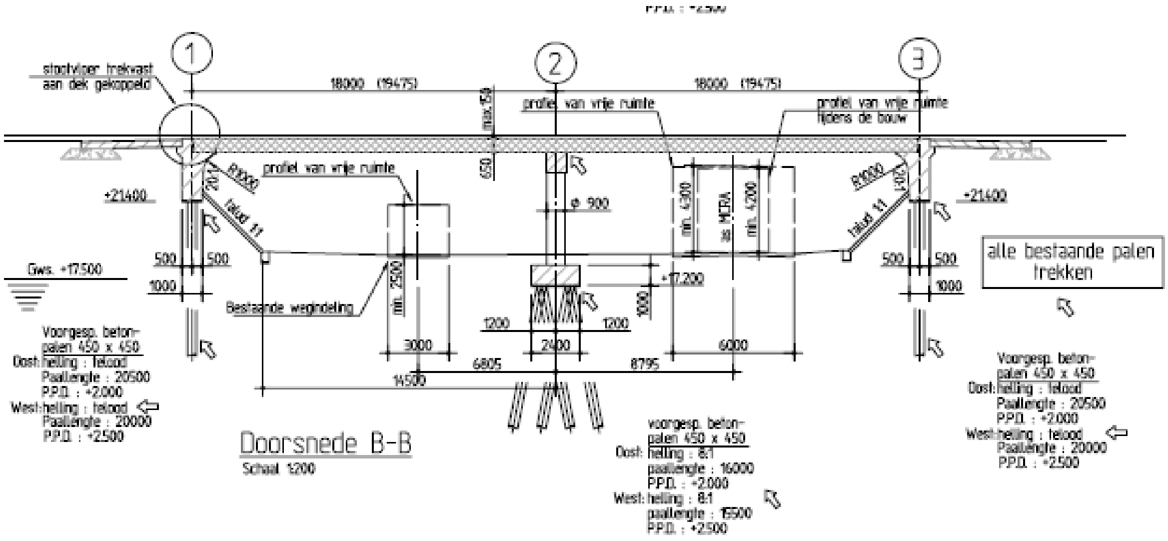
APPENDIX T : TECHNICAL DRAWING OF VIADUCT 15



Top view



Side view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West: helling : telood
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Schaal 1:200
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palen 450 x 450
Oost: helling : 8:1
paallengte : 16000
P.P.D. : +2.000
West: helling : 8:1
paallengte : 15500
P.P.D. : +2.500

Side view

APPENDIX U : OUTPUT OF TOOL

	Deck/Beam			Centre Column			Abutment			Foundation			Standard						
	Insitu (Cat I)	Worst case		Insitu (Cat I	Worst case		Insitu (Cat I)	Worst case		Pile foundation	Worst case			Worst case		Variant	Comparisson		Percentage
Weight	972	972	ton	32	32	ton	225	225	ton	507	507	ton							
Total Energy	846.164	846.164	MJ	27.683	27.683	MJ	195.871	195.871	MJ	496.967	496.967	MJ				1.566.686	1.566.686	MJ	100,0%
Total CO2	94.694	94.694	kg CO2	3.098	3.098	kg CO2	21.920	21.920	kg CO2	59.978	59.978	kg CO2				179.689	179.689	kg CO2	100,0%
Total Fuel	1.936	1.936	l	102	102	l	514	514	l	2.729	2.729	l	52	52	l	5.333	5.333	l	100,0%
Total Energy	74.704	74.704	MJ	3.884	3.884	MJ	19.697	19.697	MJ	105.708	105.708	MJ	6.150	6.150	MJ	210.143	210.143	MJ	100,0%
Total CO2	6.027	6.027	kg CO2	313	313	kg CO2	1.587	1.587	kg CO2	8.536	8.536	kg CO2	660	660	kg CO2	17.123	17.123	kg CO2	100,0%
Total Electricity	671	671	kWh	22	22	kWh	155	155	kWh	4.131	4.131	kWh				4.979	4.979	kWh	100,0%
Total Energy	2.414	2.414	MJ	79	79	MJ	559	559	MJ	38.055	38.055	MJ				41.108	41.108	MJ	100,0%
Total CO2	409	436	kg CO2	13	14	kg CO2	95	101	kg CO2	3.857	4.019	kg CO2				4.374	4.570	kg CO2	95,7%
Total Fuel	3.513	3.547	l	380	381	l	2.018	2.025	l	1.181	1.181	l				7.092	7.134	l	99,4%
Total Electricity	127	0	kWh	4	4	kWh	30	30	kWh	0	0	kWh	11.250	11.250	kWh	11.411	11.284	kWh	101,1%
Total Energy	134.523	137.640	MJ	14.767	14.794	MJ	78.411	78.602	MJ	45.844	45.844	MJ	40.500	40.500	MJ	314.045	317.381	MJ	98,9%
Total CO2	11.064	11.118	kg CO2	1.176	1.177	kg CO2	6.337	6.343	kg CO2	3.703	3.703	kg CO2	6.863	9.170	kg CO2	29.143	31.511	kg CO2	92,5%
																Total			
Total Fuel	5.450	5.483	l	482	483	l	2.531	2.539	l	3.910	3.910	l	52	52	l	12.425	12.467	l	99,7%
Total Electricity	798	671	kWh	26	26	kWh	185	185	kWh	4.131	4.131	kWh	11.250	11.250	kWh	16.390	16.263	kWh	100,8%
Total Energy	1.057.806	1.060.923	MJ	46.413	46.441	MJ	294.538	294.729	MJ	686.575	686.575	MJ	46.650	46.650	MJ	2.131.982	2.135.317	MJ	99,8%
Total CO2	112.194	112.275	kg CO2	4.600	4.602	kg CO2	29.938	29.951	kg CO2	76.074	76.236	kg CO2	7.523	9.830	kg CO2	230.329	232.893	kg CO2	98,9%
Scope 1	12.281		kg CO2	1.287		kg CO2	6.775		kg CO2	5.229		kg CO2	660		kg CO2	26.231		kg CO2	
Scope 2	78		kg CO2	3		kg CO2	18		kg CO2	0		kg CO2	6.863		kg CO2	6.961		kg CO2	
Scope 3	99.836		kg CO2	3.311		kg CO2	23.146		kg CO2	72.100		kg CO2	0		kg CO2	198.392		kg CO2	

Overview emissions (Cat I)

	Deck/Beam			Centre Column			Abutment			Foundation			Standard						
	Insitu (Cat II)	Worst case		Insitu (Cat I	Worst case		Insitu (Cat II)	Worst case		Pile foundation	Worst case			Worst case		Variant	Comparisson		Percentage
Weight	972	972	ton	32	32	ton	225	225	ton	507	507	ton							
Total Energy	846.164	846.164	MJ	27.683	27.683	MJ	195.871	195.871	MJ	496.967	496.967	MJ				1.566.686	1.566.686	MJ	100,0%
Total CO2	94.694	94.694	kg CO2	3.098	3.098	kg CO2	21.920	21.920	kg CO2	59.978	59.978	kg CO2				179.689	179.689	kg CO2	100,0%
Total Fuel	1.936	1.936	l	90	102	l	492	514	l	2.729	2.729	l	52	52	l	5.299	5.333	l	99,4%
Total Energy	74.704	74.704	MJ	3.455	3.884	MJ	18.872	19.697	MJ	105.708	105.708	MJ	6.150	6.150	MJ	208.889	210.143	MJ	99,4%
Total CO2	6.027	6.027	kg CO2	278	313	kg CO2	1.521	1.587	kg CO2	8.536	8.536	kg CO2	660	660	kg CO2	17.022	17.123	kg CO2	99,4%
Total Electricity	671	671	kWh	79	22	kWh	155	155	kWh	4.131	4.131	kWh				5.036	4.979	kWh	101,1%
Total Energy	2.414	2.414	MJ	79	79	MJ	559	559	MJ	38.055	38.055	MJ				41.108	41.108	MJ	100,0%
Total CO2	409	436	kg CO2	13	14	kg CO2	95	101	kg CO2	3.857	4.019	kg CO2				4.374	4.570	kg CO2	95,7%
Total Fuel	3.513	3.547	l	273	381	l	1.642	2.025	l	1.181	1.181	l				6.610	7.134	l	92,7%
Total Electricity	127	0	kWh	4	4	kWh	30	30	kWh	0	0	kWh	10.801	11.250	kWh	10.962	11.284	kWh	97,2%
Total Energy	134.523	137.640	MJ	10.622	14.794	MJ	63.834	78.602	MJ	45.844	45.844	MJ	38.885	40.500	MJ	293.708	317.381	MJ	92,5%
Total CO2	11.064	11.118	kg CO2	841	1.177	kg CO2	5.159	6.343	kg CO2	3.703	3.703	kg CO2	6.589	9.170	kg CO2	27.357	31.511	kg CO2	86,8%
																Total			
Total Fuel	5.450	5.483	l	364	483	l	2.134	2.539	l	3.910	3.910	l	52	52	l	11.909	12.467	l	95,5%
Total Electricity	798	671	kWh	83	26	kWh	185	185	kWh	4.131	4.131	kWh	10.801	11.250	kWh	15.999	16.263	kWh	98,4%
Total Energy	1.057.806	1.060.923	MJ	41.840	46.441	MJ	279.136	294.729	MJ	686.575	686.575	MJ	45.034	46.650	MJ	2.110.391	2.135.317	MJ	98,8%
Total CO2	112.194	112.275	kg CO2	4.231	4.602	kg CO2	28.695	29.951	kg CO2	76.074	76.236	kg CO2	7.249	9.830	kg CO2	228.442	232.893	kg CO2	98,1%
Scope 1	12.281		kg CO2	917		kg CO2	5.531		kg CO2	5.229		kg CO2	660		kg CO2	24.618		kg CO2	
Scope 2	78		kg CO2	3		kg CO2	18		kg CO2	0		kg CO2	6.589		kg CO2	6.687		kg CO2	
Scope 3	99.836		kg CO2	3.311		kg CO2	23.146		kg CO2	72.100		kg CO2	0		kg CO2	198.392		kg CO2	

Overview emissions (Cat II)

	Deck/Beam			Centre Column			Abutment			Foundation			Standard						
	Prefab onsite	Worst case		Prefab onsi	Worst case		Prefab onsite	Worst case		Pile foundation	Worst case			Worst case		Variant	Comparisson		Percentage
Weight	972	972	ton	32	32	ton	225	225	ton	507	507	ton							
Total Energy	846.164	846.164	MJ	27.683	27.683	MJ	195.871	195.871	MJ	496.967	496.967	MJ				1.566.686	1.566.686	MJ	100,0%
Total CO2	94.694	94.694	kg CO2	3.098	3.098	kg CO2	21.920	21.920	kg CO2	59.978	59.978	kg CO2				179.689	179.689	kg CO2	100,0%
Total Fuel	1.795	1.936	l	108	102	l	491	514	l	2.729	2.729	l	52	52	l	5.175	5.333	l	97,0%
Total Energy	69.235	74.704	MJ	4.113	3.884	MJ	18.854	19.697	MJ	105.708	105.708	MJ	6.150	6.150	MJ	204.059	210.143	MJ	97,1%
Total CO2	5.586	6.027	kg CO2	331	313	kg CO2	1.519	1.587	kg CO2	8.536	8.536	kg CO2	660	660	kg CO2	16.632	17.123	kg CO2	97,1%
Total Electricity	671	671	kWh	13	22	kWh	155	155	kWh	4.131	4.131	kWh				4.971	4.979	kWh	99,8%
Total Energy	2.414	2.414	MJ	79	79	MJ	559	559	MJ	38.055	38.055	MJ				41.108	41.108	MJ	100,0%
Total CO2	409	436	kg CO2	13	14	kg CO2	95	101	kg CO2	3.857	4.019	kg CO2				4.374	4.570	kg CO2	95,7%
Total Fuel	3.439	3.547	l	377	381	l	1.697	2.025	l	1.181	1.181	l				6.695	7.134	l	93,8%
Total Electricity	127	0	kWh	4	4	kWh	30	30	kWh	0	0	kWh	10.882	11.250	kWh	11.043	11.284	kWh	97,9%
Total Energy	131.638	137.640	MJ	14.657	14.794	MJ	65.976	78.602	MJ	45.844	45.844	MJ	39.175	40.500	MJ	297.290	317.381	MJ	93,7%
Total CO2	10.831	11.118	kg CO2	1.167	1.177	kg CO2	5.332	6.343	kg CO2	3.703	3.703	kg CO2	6.638	9.170	kg CO2	27.672	31.511	kg CO2	87,8%
																Total			
Total Fuel	5.234	5.483	l	485	483	l	2.189	2.539	l	3.910	3.910	l	52	52	l	11.870	12.467	l	95,2%
Total Electricity	798	671	kWh	18	26	kWh	185	185	kWh	4.131	4.131	kWh	10.882	11.250	kWh	16.014	16.263	kWh	98,5%
Total Energy	1.049.451	1.060.923	MJ	46.532	46.441	MJ	281.260	294.729	MJ	686.575	686.575	MJ	45.325	46.650	MJ	2.109.142	2.135.317	MJ	98,8%
Total CO2	111.519	112.275	kg CO2	4.609	4.602	kg CO2	28.866	29.951	kg CO2	76.074	76.236	kg CO2	7.298	9.830	kg CO2	228.367	232.893	kg CO2	98,1%
Scope 1	11.606		kg CO2	1.296		kg CO2	5.702		kg CO2	5.229		kg CO2	660		kg CO2	24.494		kg CO2	
Scope 2	78		kg CO2	3		kg CO2	18		kg CO2	0		kg CO2	6.638		kg CO2	6.736		kg CO2	
Scope 3	99.836		kg CO2	3.311		kg CO2	23.146		kg CO2	72.100		kg CO2	0		kg CO2	198.392		kg CO2	

Overview of emissions (Cat III)

	Deck/Beam			Centre Column			Abutment			Foundation			Standard						
	Prefab (Cat IV)	Worst case		Prefab (Cat	Worst case		Prefab (Cat IV	Worst case		Pile foundation	Worst case			Worst case		Variant	Comparisson		Percentage
Weight	972	972	ton	22	32	ton	156	225	ton	489	507	ton							
Total Energy	982.998	846.164	MJ	22.264	27.683	MJ	157.532	195.871	MJ	478.024	496.967	MJ				1.640.818	1.566.686	MJ	104,7%
Total CO2	120.786	94.694	kg CO2	2.736	3.098	kg CO2	19.357	21.920	kg CO2	57.650	59.978	kg CO2				200.529	179.689	kg CO2	111,6%
Total Fuel	6.180	1.936	l	154	102	l	1.025	514	l	2.609	2.729	l	52	52	l	10.021	5.333	l	187,9%
Total Energy	239.496	74.704	MJ	5.941	3.884	MJ	39.674	19.697	MJ	101.093	105.708	MJ	6.150	6.150	MJ	392.354	210.143	MJ	186,7%
Total CO2	19.340	6.027	kg CO2	479	313	kg CO2	3.203	1.587	kg CO2	8.163	8.536	kg CO2	660	660	kg CO2	31.845	17.123	kg CO2	186,0%
Total Electricity	10.015	671	kWh	213	22	kWh	1.605	155	kWh	3.938	4.131	kWh				15.771	4.979	kWh	316,7%
Total Energy	93.338	2.414	MJ	2.114	79	MJ	14.958	559	MJ	36.257	38.055	MJ				146.666	41.108	MJ	356,8%
Total CO2	9.412	436	kg CO2	213	14	kg CO2	1.508	101	kg CO2	3.676	4.019	kg CO2				14.809	4.570	kg CO2	324,0%
Total Fuel	742	3.547	l	130	381	l	519	2.025	l	1.125	1.181	l				2.517	7.134	l	35,3%
Total Electricity	0	0	kWh	0	4	kWh	0	30	kWh	0	0	kWh	2.663	11.250	kWh	2.663	11.284	kWh	23,6%
Total Energy	28.810	137.640	MJ	5.040	14.794	MJ	20.160	78.602	MJ	43.661	45.844	MJ	9.588	40.500	MJ	107.260	317.381	MJ	33,8%
Total CO2	2.327	11.118	kg CO2	407	1.177	kg CO2	1.628	6.343	kg CO2	3.527	3.703	kg CO2	1.625	9.170	kg CO2	9.514	31.511	kg CO2	30,2%
																Total			
Total Fuel	6.923	5.483	l	284	483	l	1.545	2.539	l	3.734	3.910	l	52	52	l	12.538	12.467	l	100,6%
Total Electricity	10.015	671	kWh	213	26	kWh	1.605	185	kWh	3.938	4.131	kWh	2.663	11.250	kWh	18.435	16.263	kWh	113,4%
Total Energy	1.344.643	1.060.923	MJ	35.359	46.441	MJ	232.324	294.729	MJ	659.034	686.575	MJ	15.738	46.650	MJ	2.287.098	2.135.317	MJ	107,1%
Total CO2	151.866	112.275	kg CO2	3.835	4.602	kg CO2	25.696	29.951	kg CO2	73.015	76.236	kg CO2	2.285	9.830	kg CO2	256.698	232.893	kg CO2	110,2%
Scope 1	2.412		kg CO2	425		kg CO2	1.681		kg CO2	5.048		kg CO2	660		kg CO2	10.227		kg CO2	
Scope 2	678		kg CO2	0		kg CO2	0		kg CO2	0		kg CO2	1.625		kg CO2	2.303		kg CO2	
Scope 3	149.454		kg CO2	3.410		kg CO2	24.015		kg CO2	69.224		kg CO2	0		kg CO2	246.102		kg CO2	

Overview of emissions (Cat IV)

	Deck/Beam			Centre Column			Abutment			Foundation			Standard						
	Prefab (Cat V)	Worst case		Prefab (Cat	Worst case		Prefab (Cat V)	Worst case		Pile foundation	Worst case			Worst case		Variant	Comparisson		Percentage
Weight	654	972	ton	17	32	ton	118	225	ton	367	507	ton							
Total Energy	747.051	846.164	MJ	16.797	27.683	MJ	118.849	195.871	MJ	354.893	496.967	MJ				1.237.590	1.566.686	MJ	79,0%
Total CO2	85.502	94.694	kg CO2	2.064	3.098	kg CO2	14.604	21.920	kg CO2	42.520	59.978	kg CO2				144.690	179.689	kg CO2	80,5%
Total Fuel	3.351	1.936	l	109	102	l	747	514	l	1.835	2.729	l	52	52	l	6.093	5.333	l	114,3%
Total Energy	129.927	74.704	MJ	4.166	3.884	MJ	28.737	19.697	MJ	71.094	105.708	MJ	6.150	6.150	MJ	240.073	210.143	MJ	114,2%
Total CO2	10.493	6.027	kg CO2	339	313	kg CO2	2.337	1.587	kg CO2	5.741	8.536	kg CO2	660	660	kg CO2	19.570	17.123	kg CO2	114,3%
Total Electricity	5.178	671	kWh	171	22	kWh	1.211	155	kWh	2.684	4.131	kWh				9.244	4.979	kWh	185,7%
Total Energy	47.624	2.414	MJ	1.595	79	MJ	11.285	559	MJ	24.565	38.055	MJ				85.069	41.108	MJ	206,9%
Total CO2	4.830	436	kg CO2	161	14	kg CO2	1.138	101	kg CO2	2.497	4.019	kg CO2				8.625	4.570	kg CO2	188,7%
Total Fuel	278	3.547	l	130	381	l	519	2.025	l	759	1.181	l				1.686	7.134	l	23,6%
Total Electricity	0	0	kWh	0	4	kWh	0	30	kWh	0	0	kWh	2.188	11.250	kWh	2.188	11.284	kWh	19,4%
Total Energy	10.780	137.640	MJ	5.040	14.794	MJ	20.160	78.602	MJ	29.471	45.844	MJ	7.876	40.500	MJ	73.327	317.381	MJ	23,1%
Total CO2	866	11.118	kg CO2	407	1.177	kg CO2	1.628	6.343	kg CO2	2.381	3.703	kg CO2	1.335	9.170	kg CO2	6.617	31.511	kg CO2	21,0%
																Total			
Total Fuel	3.628	5.483	l	238	483	l	1.266	2.539	l	2.595	3.910	l	52	52	l	7.780	12.467	l	62,4%
Total Electricity	5.178	671	kWh	171	26	kWh	1.211	185	kWh	2.684	4.131	kWh	2.188	11.250	kWh	11.432	16.263	kWh	70,3%
Total Energy	935.382	1.060.923	MJ	27.598	46.441	MJ	179.031	294.729	MJ	480.023	686.575	MJ	14.026	46.650	MJ	1.636.060	2.135.317	MJ	76,6%
Total CO2	101.692	112.275	kg CO2	2.971	4.602	kg CO2	19.707	29.951	kg CO2	53.138	76.236	kg CO2	1.995	9.830	kg CO2	179.503	232.893	kg CO2	77,1%
Scope 1	880		kg CO2	423		kg CO2	1.681		kg CO2	3.868		kg CO2	660		kg CO2	7.511		kg CO2	
Scope 2	0		kg CO2	0		kg CO2	0		kg CO2	0		kg CO2	1.335		kg CO2	1.335		kg CO2	
Scope 3	100.763		kg CO2	2.548		kg CO2	18.026		kg CO2	50.526		kg CO2	0		kg CO2	171.863		kg CO2	

Overview of emissions (Cat V)

APPENDIX V : RESULTS PER ELEMENT

This chapter discusses the emission of each construction method in comparison to the worst-case scenario. Figure V.1 and Figure V.2 compare all construction methods. In Appendix T a complete overview of emissions is given. Appendix Y shows the distribution of energy and CO_2 if a structure was constructed with only one construction method.

From the tables it can be concluded that the two biggest consumers of energy are the deck and the foundation. In Figure V.1 and Figure V.2 a visual overview is given of the energy consumption and CO_2 emission of the different elements.

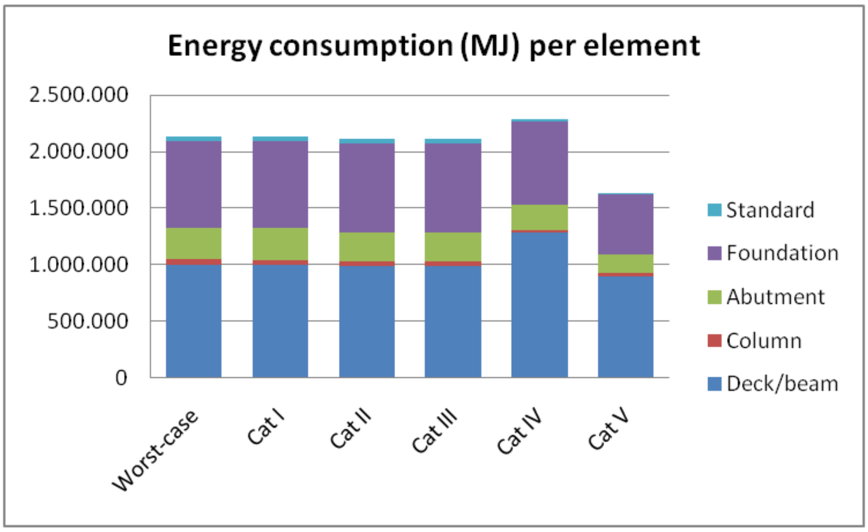


Figure V.1: Overview of distribution of energy consumption over elements

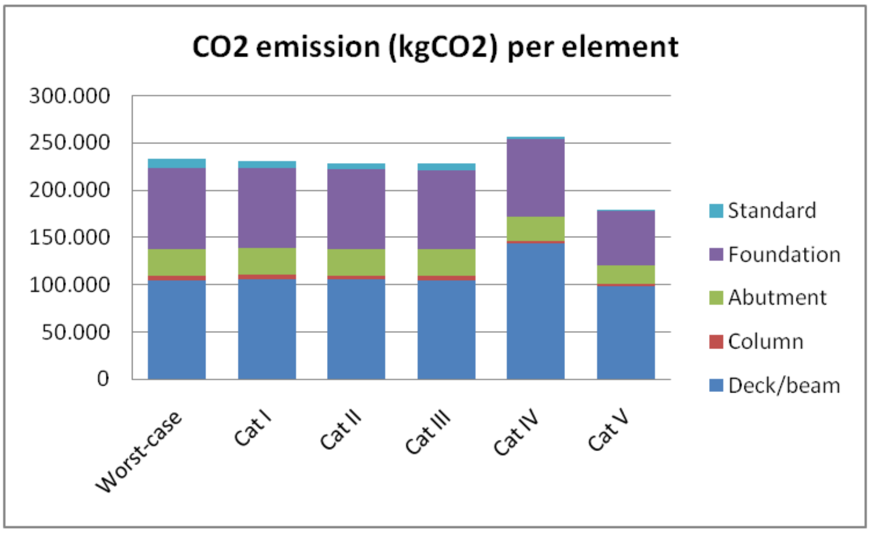


Figure V.2: Overview of distribution of CO_2 emission over elements

The next (sub) paragraphs discuss the results more thoroughly. All the comparisons are made with, the previously formulated, worst-case scenario. The results will show what the real differences are. The differences between different construction methods are discussed. In each comparison only one construction method is changed and all other elements of that variant are constructed with insitu. This makes sure the elements can be discussed separately; the influence of weight reduction and project time on the emissions will be discussed in chapter 9.

Results deck/beam

The deck is one of the biggest contributors to the energy consumption and CO_2 emission of all the elements.

Onsite (Cat I)

Category I is the category which is the closest to the worst-case scenario. The output of the model shows this:

		Deck/Beam		
		Insitu (Cat I)	Worst case	
Material	Weight	972	972	ton
	Total Energy	846.164	846.164	MJ
	Total CO2	94.694	94.694	kg CO2
Transport				
	Total Fuel	1.936	1.936	l
	Total Energy	74.704	74.704	MJ
	Total CO2	6.027	6.027	kg CO2
Factory				
	Total Electricity	671	671	kWh
	Total Energy	2.414	2.414	MJ
	Total CO2	409	436	kg CO2
Onsite				
	Total Fuel	3.513	3.547	l
	Total Electricity	127	0	kWh
	Total Energy	134.523	137.640	MJ
	Total CO2	11.064	11.118	kg CO2
Total				
	Total Fuel	5.450	5.483	l
	Total Electricity	798	671	kWh
	Total Energy	1.057.806	1.060.923	MJ
	Total CO2	112.194	112.275	kg CO2

Table V.1: Overview of energy consumption and CO_2 emission of a deck (Cat I)

There is only a small difference (<0,1%) in CO_2 emission. There is a small difference in energy; this difference originates from the electricity that is generated onsite.

Onsite (Cat II)

The difference between Cat II and the worst-case scenario is the same as Cat I. System formwork is used, but there is no difference because system formwork has only benefits when multiple elements are produced. This shows in the result of the construction of the deck:

		Deck/Beam	
		Insitu (Cat II)	Worst case
Material	Weight	972	972
	Total Energy	846.164	846.164
	Total CO2	94.694	94.694
Transport			
	Total Fuel	1.936	1.936
	Total Energy	74.704	74.704
	Total CO2	6.027	6.027
Factory			
	Total Electricity	671	671
	Total Energy	2.414	2.414
	Total CO2	409	436
Onsite			
	Total Fuel	3.513	3.547
	Total Electricity	127	0
	Total Energy	134.523	137.640
	Total CO2	11.064	11.118
Total			
	Total Fuel	5.450	5.483
	Total Electricity	798	671
	Total Energy	1.057.806	1.060.923
	Total CO2	112.194	112.275

Table V.2: Overview of energy consumption and CO_2 emission of a deck (Cat II)

The emission is the same as with Cat I. Because the assumed calculation values for the deck are the same. As stated earlier, constructing a deck with standard formwork (Cat II) is not common practise. Only when numerous decks with the same dimensions are required, does standard formwork has its benefits.

Prefab onsite (Cat III)

One of the problems when constructing a deck insitu is the build of the falsework to support the structure. This takes time, manpower and crane time. Constructing the deck onsite and hoisting it in place, does not require falsework. Extra onsite emissions are required to hoist the deck into place. Table V.3 shows an overview of the emissions.

		Deck/Beam	
		Prefab onsite (Cat III)	Worst case
Material	Weight	972	972
	Total Energy	846.164	846.164
	Total CO2	94.694	94.694
Transport			
	Total Fuel	1.795	1.936
	Total Energy	69.235	74.704
	Total CO2	5.586	6.027
Factory			
	Total Electricity	671	671
	Total Energy	2.414	2.414
	Total CO2	409	436
Onsite			
	Total Fuel	3.439	3.547
	Total Electricity	127	0
	Total Energy	131.638	137.640
	Total CO2	10.831	11.118
Total			
	Total Fuel	5.234	5.483
	Total Electricity	798	671
	Total Energy	1.049.451	1.060.923
	Total CO2	111.519	112.275

Table V.3: Overview of energy consumption and CO_2 emission of a deck (Cat III)

Prefabrication onsite emits less CO_2 and requires less energy than constructing a deck with insitu (Cat I and Cat II).The difference in emission of CO_2 and energy usage with the worst-case scenario is 1%. There is less fuel consumed and because of cleaner energy less CO_2 is emitted. It is important to remark that constructing prefab onsite (especially a deck) is always done to overcome project specific problems; for example the closing of a road or railway. If these types of project specific problems occur, different tradeoffs are made. Manpower and equipment are less important, but time is the leading factor. In a real situation, onsite emissions would therefore be higher than the model shows. Extra equipment and manpower would be available to make sure the deadline is met.

Prefab (Cat IV)

The quantity of concrete used in a deck with project specific prefab is the same as in a deck of insitu concrete (C35/C45), only in Cat IV it is constructed with C53/C65 concrete. This type of concrete emits more CO_2/m^3 than C35/C45, the emissions will differentiate from the results of Cat I – Cat III. Because of the assumption in chapter 6, there is no reduction of the usage of higher strength concrete because the quantity of reinforcement is leading.

		Deck/Beam	
		Prefab (Cat IV)	Worst case
Material	Weight	972	972
	Total Energy	982.998	846.164
	Total CO2	120.786	94.694
Transport			
	Total Fuel	6.180	1.936
	Total Energy	239.496	74.704
	Total CO2	19.340	6.027
Factory			
	Total Electricity	10.015	671
	Total Energy	93.338	2.414
	Total CO2	9.412	436
Onsite			
	Total Fuel	742	3.547
	Total Electricity	0	0
	Total Energy	28.810	137.640
	Total CO2	2.327	11.118
Total			
	Total Fuel	6.923	5.483
	Total Electricity	10.015	671
	Total Energy	1.344.643	1.060.923
	Total CO2	151.866	112.275

Table V.4: Overview of energy consumption and CO_2 emission of a deck (Cat IV)

The result shows that more energy is required in the construction of Cat IV than the worst case scenario. The difference in energy usage is 27%, in CO_2 emission 35%. Because more energy is required in the production of higher strength concrete while no reduction of concrete is obtained. The implementation of high strength concrete in decks should therefore be only be applied if energy and CO_2 reduction is not an issue or if there is a valid argument to use it. Whether or not a deck could be designed slimmer with the usage of higher strength concrete is something which should be reviewed further. If the CO_2 emission of the construction material would be left out the equation there is still more CO_2 emitted than in the worst-case scenario. Especially transport contributes a great deal to this. The fact that elements are produced in a factory and post tensioned onsite also adds to the emissions.

Prefab (Cat V)

Constructing a deck with prefab beams is a method applied often in viaducts. Because box beams are used, a reduction in material occurs.

		Deck/Beam	
		Prefab (Cat V)	Worst case
Material	Weight	654	972
	Total Energy	747.051	846.164
	Total CO2	85.502	94.694
Transport			
	Total Fuel	3.351	1.936
	Total Energy	129.927	74.704
	Total CO2	10.493	6.027
Factory			
	Total Electricity	5.178	671
	Total Energy	47.624	2.414
	Total CO2	4.830	436
Onsite			
	Total Fuel	278	3.547
	Total Electricity	0	0
	Total Energy	10.780	137.640
	Total CO2	866	11.118
Total			
	Total Fuel	3.628	5.483
	Total Electricity	5.178	671
	Total Energy	935.382	1.060.923
	Total CO2	101.692	112.275

Table V.5: Overview of energy consumption and CO2 emission of a deck (Cat V)

The quantities in Table V.5 show the influence of weight reduction. Because C53/C65 concrete is used (which contains CEM I) the reduction in emissions is less than the decrease in material would suggest (10% in CO_2). The longer travel route causes more CO_2 is emission during transport. Onsite there is a considerable energy reduction (92%). The production of beam in the factory results in a higher energy requirement in the factory. Both the usage of less concrete and the process are more efficient than the worst-case scenario.

Conclusion deck/beam

The emission of a construction in Cat I, II and III are very comparable to each other. The emission of the production of material is the same with in all the insitu construction methods. Constructing a deck with project specific formwork (Cat IV) emits more CO_2 than all the other categories. The construction of a project specific deck is an outsider, more emissions and energy is required, this is because high strength concrete is used, but no structural gain is acquired by that. Cat V achieves a reduction of about 10% on both energy consumption and CO_2 emission. The distribution of the emissions over the different sectors in Cat I- Cat III are quite similar. The built up of emissions of prefab (Cat V) is different in comparison with the insitu construction methods. There is a considerable reduction in CO_2 emission with the onsite emissions and in the material. Transport and factory emissions are higher than the insitu variants. Table V.6 shows an overview of the chosen construction methods.

Deck/Beams				
	MJ	Similarity	kgCO2	Similarity
Worst-case	1.061.000	100%	112.300	100%
Cat I	1.058.000	100%	112.200	100%
Cat II	1.058.000	100%	112.200	100%
Cat III	1.049.000	99%	111.500	99%
Cat IV	1.345.000	127%	151.900	135%
Cat V	935.000	88%	101.700	91%

Table V.6: Overview of energy use and CO_2 emissions of Deck/beams

Results columns

This paragraph discusses the emissions of the columns. The deck will be constructed in insitu to make a fair comparison. Columns, abutments and foundation get different dimensions when weight reductions occur. In chapter 9 the influence of weight reduction on the emissions of the structure is discussed. The comparison is, again, made with the worst-case scenario. A total overview of the emissions can be found in Appendix V.

Insitu (Cat I)

There is only a small difference between insitu Cat I and the worst-case scenario. An overview of the total emissions can be seen in Table V.7.

		Centre Column		
		Insitu (Cat I)	Worst case	
Material	Weight	32	32	ton
	Total Energy	27.683	27.683	MJ
	Total CO2	3.098	3.098	kg CO2
Transport				
	Total Fuel	102	102	l
	Total Energy	3.884	3.884	MJ
	Total CO2	313	313	kg CO2
Factory				
	Total Electricity	22	22	kWh
	Total Energy	79	79	MJ
	Total CO2	13	14	kg CO2
Onsite				
	Total Fuel	380	381	l
	Total Electricity	4	4	kWh
	Total Energy	14.767	14.794	MJ
	Total CO2	1.176	1.177	kg CO2
Total				
	Total Fuel	482	483	l
	Total Electricity	26	26	kWh
	Total Energy	46.413	46.441	MJ
	Total CO2	4.600	4.602	kg CO2

Table V.7: Overview of emissions of columns (Cat I)

The relative emissions of the column are in the same league as with the difference in the construction with the deck. The difference between the worst-case and Cat I is less than 0,1% of the CO_2 emissions. Because the construction method is the same no big differences occur.

Insitu (Cat II)

Cat II has an advantage over the worst-case scenario because it reuses its formwork. This results in less crane time and therefore fewer emissions. The required transport is also smaller but the reduction achieved onsite are more considerable. A total reduction of 6% in CO_2 emission and 10% in energy consumption is obtained.

		Centre Column		
		Insitu (Cat II)	Worst case	
Material	Weight	32	32	ton
	Total Energy	27.683	27.683	MJ
	Total CO2	3.098	3.098	kg CO2
Transport				
	Total Fuel	90	102	l
	Total Energy	3.455	3.884	MJ
	Total CO2	278	313	kg CO2
Factory				
	Total Electricity	79	22	kWh
	Total Energy	79	79	MJ
	Total CO2	13	14	kg CO2
Onsite				
	Total Fuel	273	381	l
	Total Electricity	4	4	kWh
	Total Energy	10.622	14.794	MJ
	Total CO2	841	1.177	kg CO2
Total				
	Total Fuel	364	483	l
	Total Electricity	83	26	kWh
	Total Energy	41.840	46.441	MJ
	Total CO2	4.231	4.602	kg CO2

Table V.8: Overview of emissions of columns (Cat II)

The decision to construct with prefabricated formwork has a direct effect on the emissions of the project. There is fewer transport required and, because the formwork is reused, less crane time is required, there are less emissions onsite.

Prefab onsite (Cat III)

Remarkable is that the emissions of Cat III are higher than the worst-case scenario. Because more crane time is required than with the construction of the worst-case scenario. These extra work hours translates in more emissions due to transport. Even though reductions are made due to the reuse of formwork, this does not weigh up to the extra emissions due to additional crane time and extra transport.

		Centre Column		
		Prefab onsite (Cat III)	Worst case	
Material	Weight	32	32	ton
	Total Energy	27.683	27.683	MJ
	Total CO2	3.098	3.098	kg CO2
Transport				
	Total Fuel	108	102	l
	Total Energy	4.113	3.884	MJ
	Total CO2	331	313	kg CO2
Factory				
	Total Electricity	13	22	kWh
	Total Energy	79	79	MJ
	Total CO2	13	14	kg CO2
Onsite				
	Total Fuel	377	381	l
	Total Electricity	4	4	kWh
	Total Energy	14.657	14.794	MJ
	Total CO2	1.167	1.177	kg CO2
Total				
	Total Fuel	485	483	l
	Total Electricity	18	26	kWh
	Total Energy	46.532	46.441	MJ
	Total CO2	4.609	4.602	kg CO2

Table V.9: Overview of emissions of columns (Cat III)

Prefab (Cat IV)

Because prefab is constructed in C53/C65 instead of C35/C45 the columns are constructed slimmer. This gives a reduction in material. This influences the quantity of transport. Because the elements are prefabricated there is less energy required onsite, the energy required in the factory is higher.

		Centre Column		
		Prefab (Cat IV)	Worst case	
Material	Weight	22	32	ton
	Total Energy	22.264	27.683	MJ
	Total CO2	2.736	3.098	kg CO2
Transport				
	Total Fuel	154	102	l
	Total Energy	5.941	3.884	MJ
	Total CO2	479	313	kg CO2
Factory				
	Total Electricity	213	22	kWh
	Total Energy	2.114	79	MJ
	Total CO2	213	14	kg CO2
Onsite				
	Total Fuel	130	381	l
	Total Electricity	0	4	kWh
	Total Energy	5.040	14.794	MJ
	Total CO2	407	1.177	kg CO2
Total				
	Total Fuel	284	483	l
	Total Electricity	213	26	kWh
	Total Energy	35.359	46.441	MJ
	Total CO2	3.835	4.602	kg CO2

Table V.10: Overview of emissions of columns (Cat IV)

It can be concluded that the usage of high strength concrete is beneficial in columns; less energy is required in the production of the material. The reduction of material has a positive influence on the emissions of transport, but because the travel distances are larger the emissions are still bigger than with insitu. The work onsite is reduced considerable with the usage of prefab. A total reduction of 17% CO_2 is achieved in the total production and construction process, 12% due to fewer material and 27% because a more efficient process.

Prefab (Cat V)

The difference between Cat V and the worst-case scenario is comparable to the difference between Cat IV and the worst-case scenario. The only difference in the process is the production of the elements in the factory. Because Cat V is more automated, the production in the factory will go faster and will require less manpower. This has its affects on the quantity of transport required. The same values are used for the energy consumption in factories, these values are the same. The total reduction in CO_2 is 17%; the reduction in energy is 25%.

		Centre Column		
		Prefab (Cat V)	Worst case	
Material	Weight	22	32	ton
	Total Energy	22.264	27.683	MJ
	Total CO2	2.736	3.098	kg CO2
Transport				
	Total Fuel	142	102	l
	Total Energy	5.458	3.884	MJ
	Total CO2	444	313	kg CO2
Factory				
	Total Electricity	227	22	kWh
	Total Energy	2.114	79	MJ
	Total CO2	213	14	kg CO2
Onsite				
	Total Fuel	130	381	l
	Total Electricity	0	4	kWh
	Total Energy	5.040	14.794	MJ
	Total CO2	407	1.177	kg CO2
Total				
	Total Fuel	272	483	l
	Total Electricity	227	26	kWh
	Total Energy	34.876	46.441	MJ
	Total CO2	3.800	4.602	kg CO2

Table V.11: Overview of emissions of columns (Cat V)

Conclusions of columns

The most important conclusion in this paragraph is that it is beneficial to use high strength concrete when structural gain can be achieved. Furthermore it is beneficial to use prefabricate elements, because the extra emissions of transport and in the factory weigh up to the reductions that are acquired onsite. An overview of the results can be seen in Table V.12. The fact that prefab elements emit less CO_2 and use less energy than insitu elements is the result of less material and a more efficient process.

	Columns			
	MJ	Similarity	kgCO2	Similarity
Worst-case	46.400	100%	4.600	100%
Cat I	46.400	100%	4.600	100%
Cat II	41.800	90%	4.200	91%
Cat III	46.500	100%	4.600	100%
Cat IV	35.400	76%	3.800	83%
Cat V	34.900	75%	3.800	83%

Table V.12: Overview of electricity use and CO_2 emissions of columns

Result of abutment

The differences between the different construction methods are expected to be in the same line as the columns. The same considerations are used as with the columns.

Insitu (Cat I)

There is little difference between the worst-case emissions and Insitu (Cat I) emissions. The relationship between the emissions of the worst-case scenario and Cat I are the same as the deck and columns

		Abutment		
		Insitu (Cat I)	Worst case	
Material	Weight	225	225	ton
	Total Energy	195.871	195.871	MJ
	Total CO2	21.920	21.920	kg CO2
Transport				
	Total Fuel	514	514	l
	Total Energy	19.697	19.697	MJ
	Total CO2	1.587	1.587	kg CO2
Factory				
	Total Electricity	155	155	kWh
	Total Energy	559	559	MJ
	Total CO2	95	101	kg CO2
Onsite				
	Total Fuel	2.018	2.025	l
	Total Electricity	30	30	kWh
	Total Energy	78.411	78.602	MJ
	Total CO2	6.337	6.343	kg CO2
Total				
	Total Fuel	2.531	2.539	l
	Total Electricity	185	185	kWh
	Total Energy	294.538	294.729	MJ
	Total CO2	29.938	29.951	kg CO2

Table V.13: Overview of emissions of abutments (Cat I)

Insitu (Cat II)

The CO_2 emissions in Cat II are about 4% less when compared to the worst-case scenario. There is a reduction of 5% of energy compared to the worst-case scenario. These reductions originate because less energy is required onsite in transport and in the concrete factory. The gains originate from reusing formwork.

		Abutment		
		Insitu (Cat II)	Worst case	
Material	Weight	225	225	ton
	Total Energy	195.871	195.871	MJ
	Total CO2	21.920	21.920	kg CO2
Transport				
	Total Fuel	492	514	l
	Total Energy	18.872	19.697	MJ
	Total CO2	1.521	1.587	kg CO2
Factory				
	Total Electricity	155	155	kWh
	Total Energy	559	559	MJ
	Total CO2	95	101	kg CO2
Onsite				
	Total Fuel	1.642	2.025	l
	Total Electricity	30	30	kWh
	Total Energy	63.834	78.602	MJ
	Total CO2	5.159	6.343	kg CO2
Total				
	Total Fuel	2.134	2.539	l
	Total Electricity	185	185	kWh
	Total Energy	279.136	294.729	MJ
	Total CO2	28.695	29.951	kg CO2

Table V.14: Overview of emissions of abutments (Cat II)

Prefab onsite (Cat III)

Constructing prefab onsite gives a little bit of reduction in energy and CO_2 in comparison with the worst-case scenario. Mainly because of less transport and less energy use onsite. The crane is used less because formwork is reused.

		Abutment		
		Prefab onsite (Cat III)	Worst case	
Material	Weight	225	225	ton
	Total Energy	195.871	195.871	MJ
	Total CO2	21.920	21.920	kg CO2
Transport				
	Total Fuel	491	514	l
	Total Energy	18.854	19.697	MJ
	Total CO2	1.519	1.587	kg CO2
Factory				
	Total Electricity	155	155	kWh
	Total Energy	559	559	MJ
	Total CO2	95	101	kg CO2
Onsite				
	Total Fuel	1.697	2.025	l
	Total Electricity	30	30	kWh
	Total Energy	65.976	78.602	MJ
	Total CO2	5.332	6.343	kg CO2
Total				
	Total Fuel	2.189	2.539	l
	Total Electricity	185	185	kWh
	Total Energy	281.260	294.729	MJ
	Total CO2	28.866	29.951	kg CO2

Table V.15: Overview of emissions of abutments (Cat III)

Prefab (Cat IV)

Considering only the material use there is 20% less energy consumption and 12% less CO_2 emission. Over the whole production process this is respectively 21% and 14%.

		Abutment		
		Prefab (Cat IV)	Worst case	
Material	Weight	156	225	ton
	Total Energy	157.532	195.871	MJ
	Total CO2	19.357	21.920	kg CO2
Transport				
	Total Fuel	1.025	514	l
	Total Energy	39.674	19.697	MJ
	Total CO2	3.203	1.587	kg CO2
Factory				
	Total Electricity	1.605	155	kWh
	Total Energy	14.958	559	MJ
	Total CO2	1.508	101	kg CO2
Onsite				
	Total Fuel	519	2.025	l
	Total Electricity	0	30	kWh
	Total Energy	20.160	78.602	MJ
	Total CO2	1.628	6.343	kg CO2
Total				
	Total Fuel	1.545	2.539	l
	Total Electricity	1.605	185	kWh
	Total Energy	232.324	294.729	MJ
	Total CO2	25.696	29.951	kg CO2

Table V.16: Overview of emissions of abutments (Cat IV)

Prefab (Cat V)

The same conclusions can be drawn up from Cat V as from Cat IV. But the emissions are reduced even further. A total reduction of energy of 22% and a reduction of 15% of CO_2 can be obtained.

		Abutment		
		Prefab (Cat V)	Worst case	
Material	Weight	156	225	ton
	Total Energy	157.532	195.871	MJ
	Total CO2	19.357	21.920	kg CO2
Transport				
	Total Fuel	984	514	l
	Total Energy	37.877	19.697	MJ
	Total CO2	3.080	1.587	kg CO2
Factory				
	Total Electricity	1.605	155	kWh
	Total Energy	14.958	559	MJ
	Total CO2	1.508	101	kg CO2
Onsite				
	Total Fuel	519	2.025	l
	Total Electricity	0	30	kWh
	Total Energy	20.160	78.602	MJ
	Total CO2	1.628	6.343	kg CO2
Total				
	Total Fuel	1.503	2.539	l
	Total Electricity	1.605	185	kWh
	Total Energy	230.527	294.729	MJ
	Total CO2	25.574	29.951	kg CO2

Table V.17: Overview of emissions of abutments (Cat V)

Conclusion of abutments

Almost the same conclusions can be drawn up as can be done from the columns; huge reductions of emissions can be achieved when elements are prefabricated with high strength concrete. The gains are nonetheless smaller than with the construction of columns. One of the reasons for that is that (relatively) more work onsite is required and formwork is reused only two times instead of four times with the columns. The overview of the emissions of CO_2 and energy use can be found in Table V.18

	Abutments			
	MJ	Similarity	kgCO2	Similarity
Worst-case	294.700	100%	30.000	100%
Cat I	294.500	100%	29.900	100%
Cat II	279.100	95%	28.700	96%
Cat III	281.300	95%	28.900	96%
Cat IV	232.300	79%	25.700	86%
Cat V	230.500	78%	25.600	85%

Table V.18: Overview of electricity use and CO_2 emission of abutments

Foundation

The QST discusses only one type of foundation, prefab foundation piles. The difference in CO_2 emissions with the worst-case scenario is small (<1%). Of course there is no difference in of energy required.

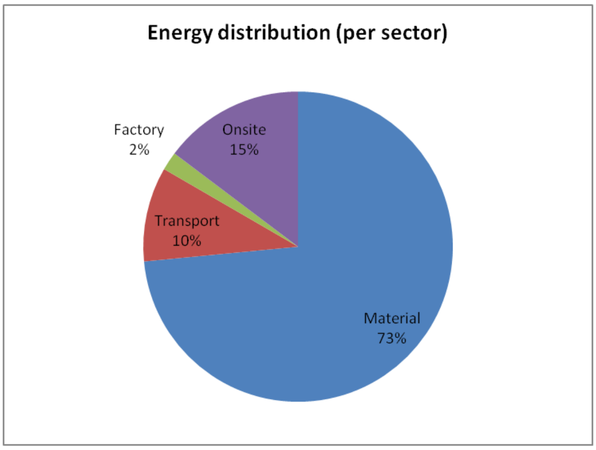
	Foundation		
	Pile foundation	Worst case	
Weight	507	507	ton
Total Energy	496.967	496.967	MJ
Total CO2	59.978	59.978	kg CO2
Total Fuel	2.729	2.729	l
Total Energy	105.708	105.708	MJ
Total CO2	8.536	8.536	kg CO2
Total Electricity	4.131	4.131	kWh
Total Energy	38.055	38.055	MJ
Total CO2	3.857	4.019	kg CO2
Total Fuel	1.181	1.181	l
Total Electricity	0	0	kWh
Total Energy	45.844	45.844	MJ
Total CO2	3.703	3.703	kg CO2
Total Fuel	3.910	3.910	l
Total Electricity	4.131	4.131	kWh
Total Energy	686.575	686.575	MJ
Total CO2	76.074	76.236	kg CO2

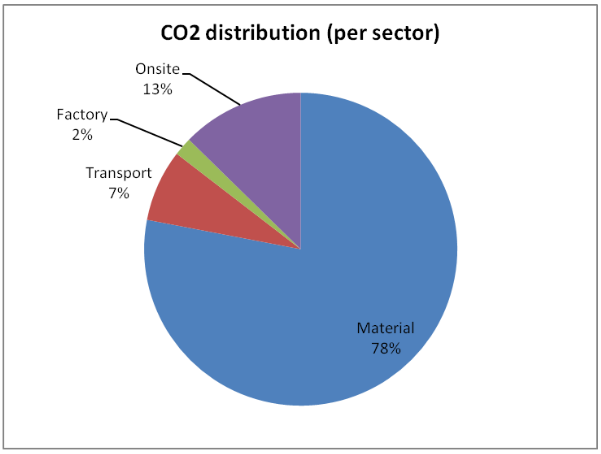
TableV.19: Overview of emissions of the foundation

APPENDIX W : OVERVIEW OF ENERGY CONSUMPTION AND CO_2 EMISSIONS PER ELEMENT

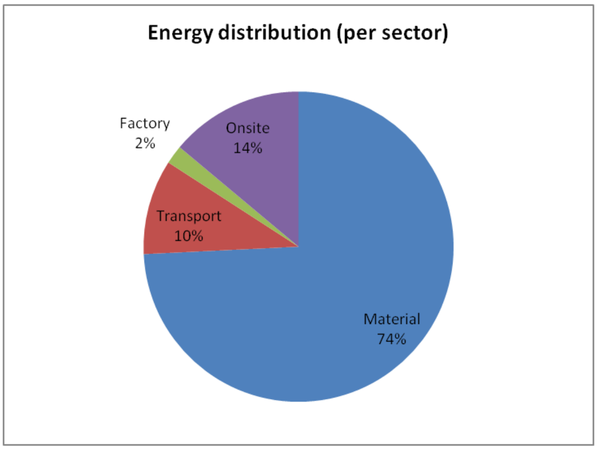
	Deck/Beams				Columns				Abutments				Average	
	MJ	Difference	kgCO2	Difference	MJ	Difference	kgCO2	Difference	MJ	Difference	kgCO2	Difference	MJ	kgCO2
Worst-case	1.061.000	100%	112.300	100%	46.400	100%	4.600	100%	294.700	100%	30.000	100%	100%	100%
Cat I	1.058.000	100%	112.200	100%	46.400	100%	4.600	100%	294.500	100%	29.900	100%	100%	100%
Cat II	1.058.000	100%	112.200	100%	41.800	90%	4.200	92%	279.100	95%	28.700	96%	98%	99%
Cat III	1.049.000	99%	111.500	99%	46.500	100%	4.600	100%	281.300	95%	28.900	96%	98%	99%
Cat IV	1.345.000	127%	151.900	135%	35.400	76%	3.800	83%	232.300	79%	25.700	86%	115%	124%
Cat V	935.000	88%	101.700	91%	34.900	75%	3.800	83%	230.500	78%	25.600	85%	86%	89%

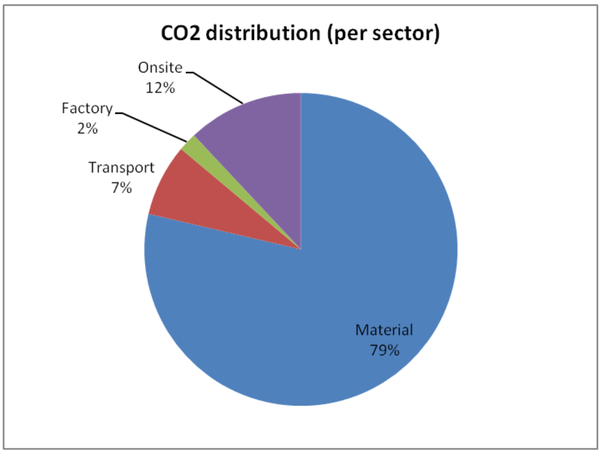
APPENDIX X : OVERVIEW OF EMISSIONS OVER DIFFERENT SECTORS



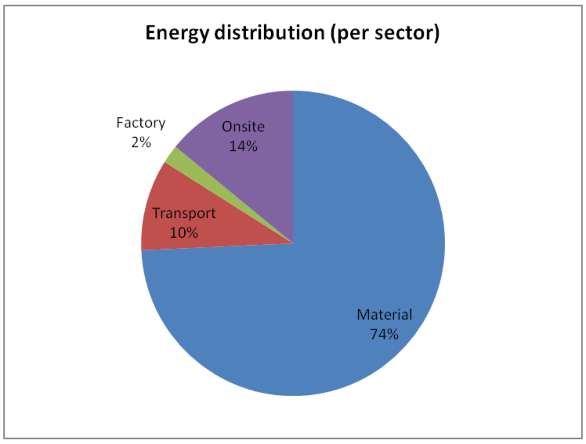


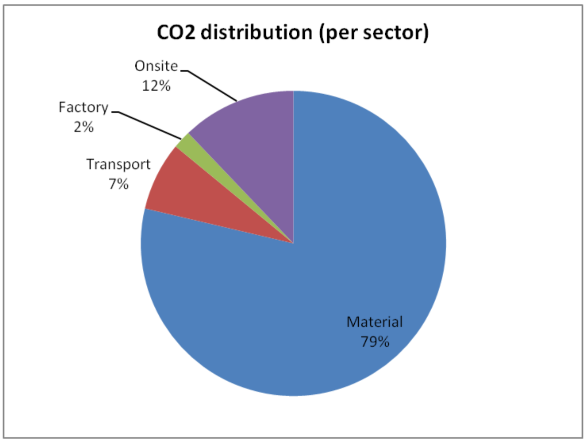
Cat I



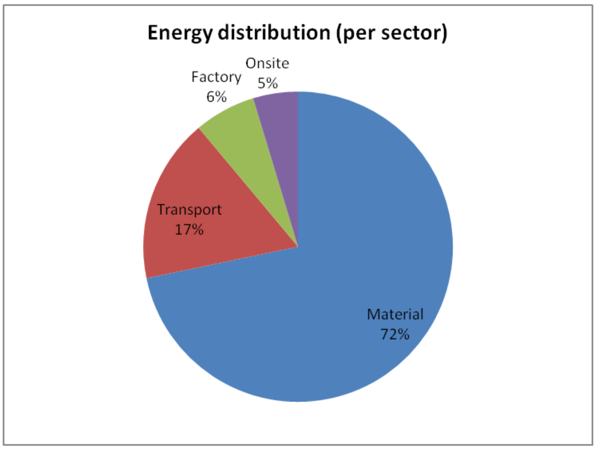


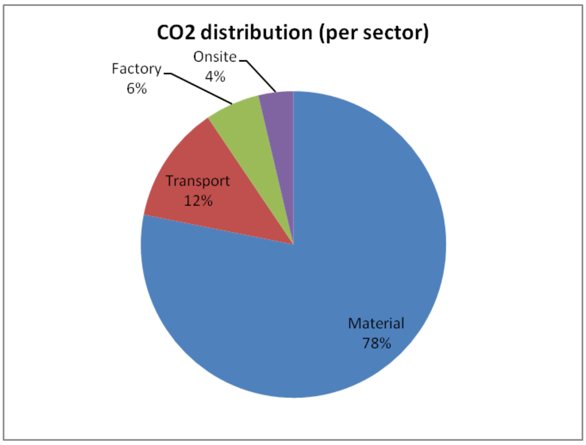
Cat II



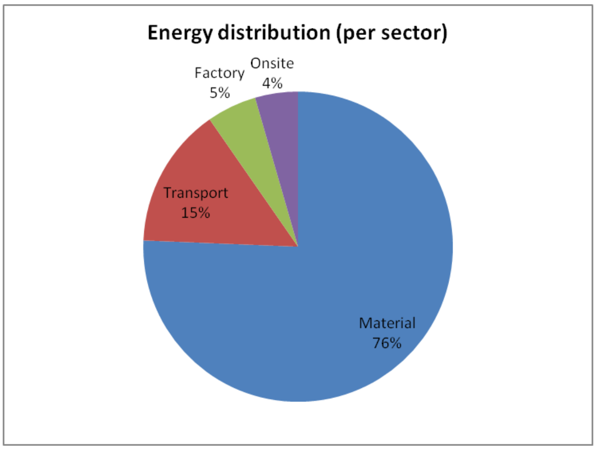


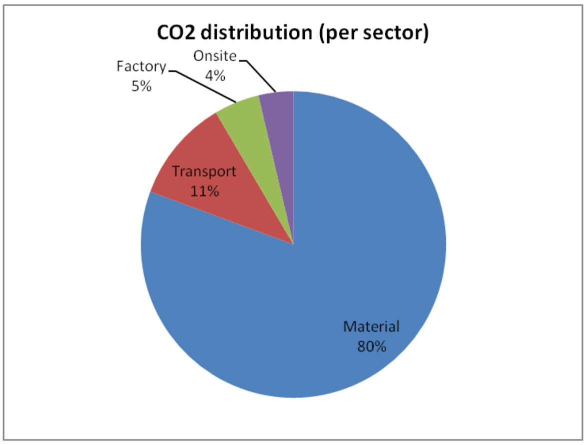
Cat III


Energy distribution (per sector)
Onsite 5%
Factory 6%
Transport 17%
Material 72%


CO2 distribution (per sector)
Onsite 4%
Factory 6%
Transport 12%
Material 78%

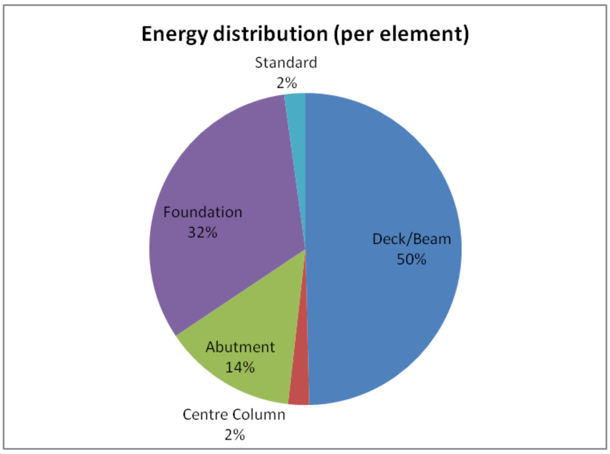
Cat IV

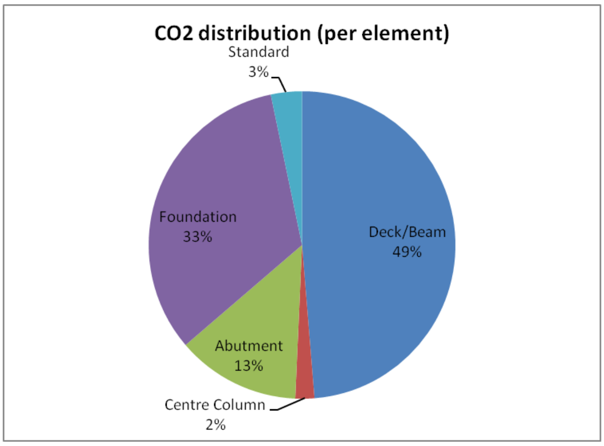

Energy distribution (per sector)
Onsite 4%
Factory 5%
Transport 15%
Material 76%


CO2 distribution (per sector)
Onsite 4%
Factory 5%
Transport 11%
Material 80%

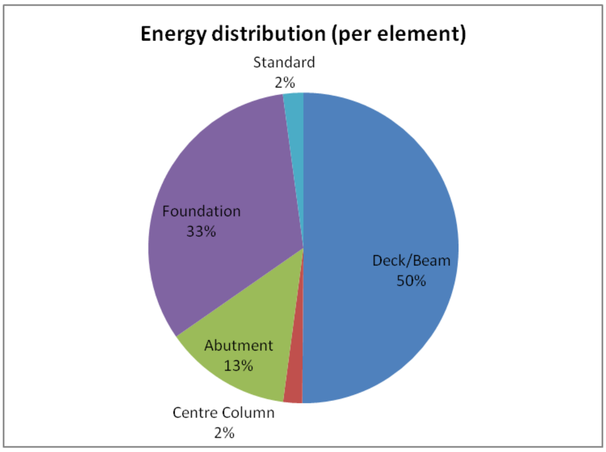
Cat V

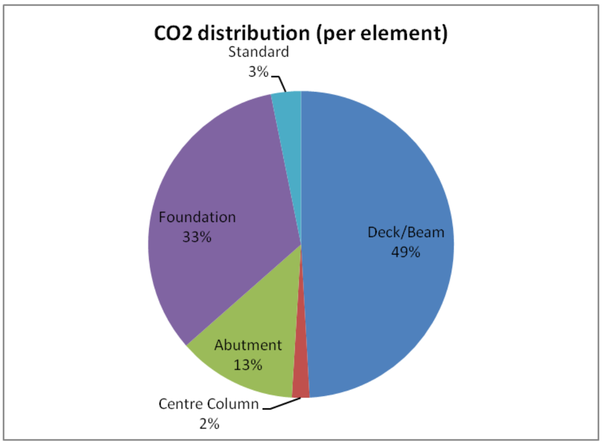
APPENDIX Y : OVERVIEW OF DISTRIBUTION OF ENERGY AND CO_2 PER ELEMENT



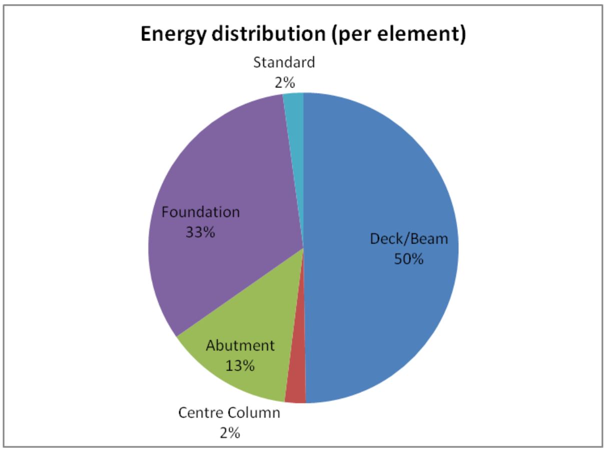


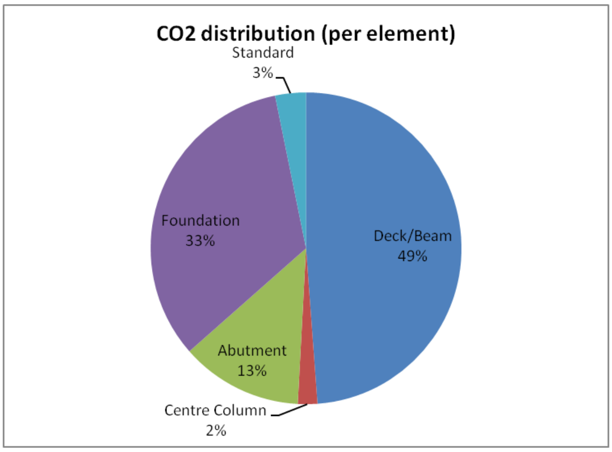
Energy consumption and CO_2 emission per element (Cat I)



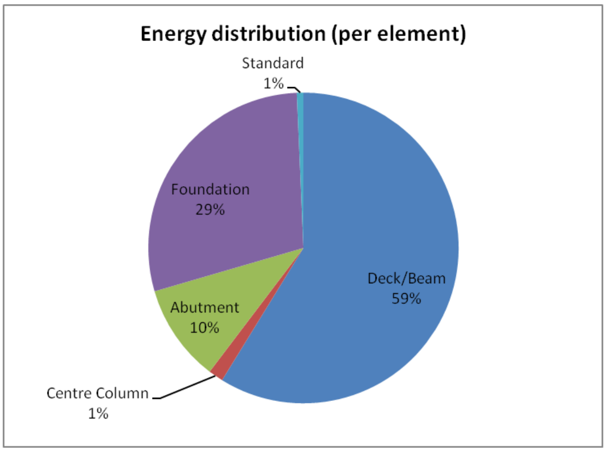


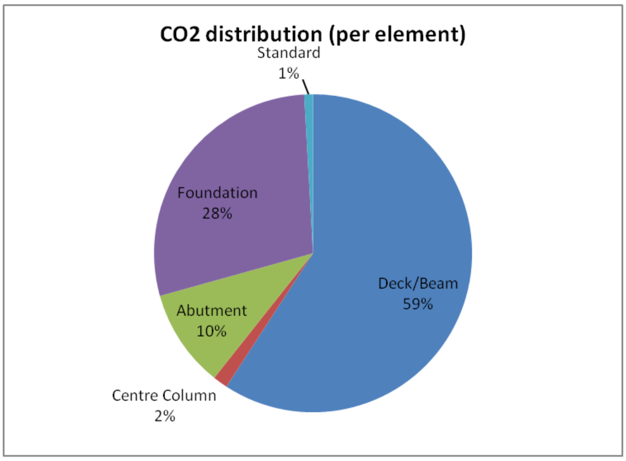
Energy consumption and CO_2 emission per element (Cat II)



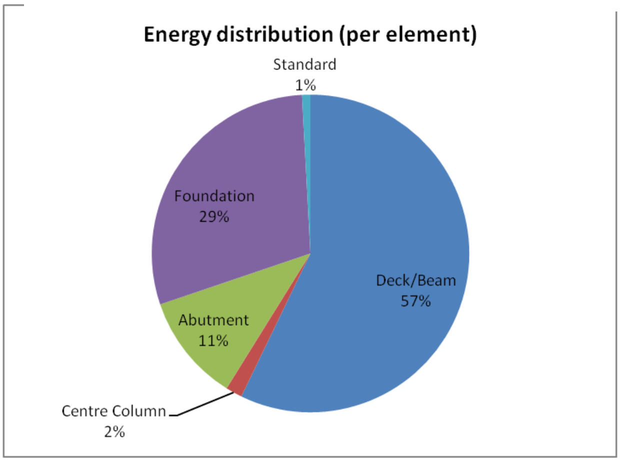


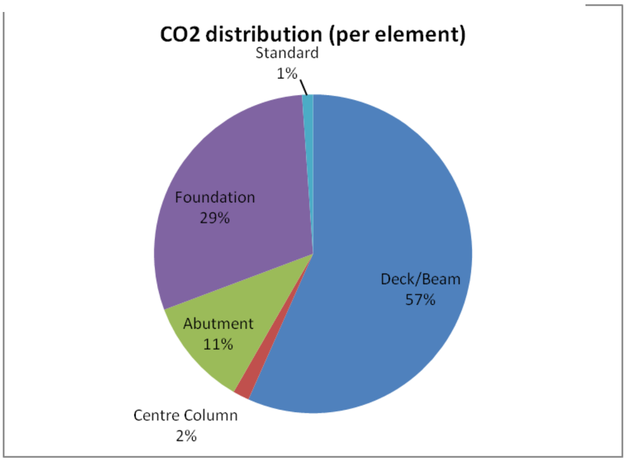
Energy consumption and CO_2 emission per element (Cat III)





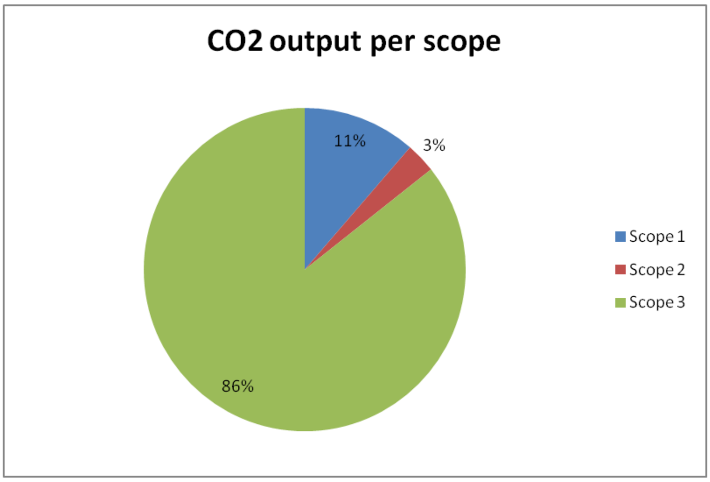
Energy consumption and CO_2 emission per element (Cat IV)



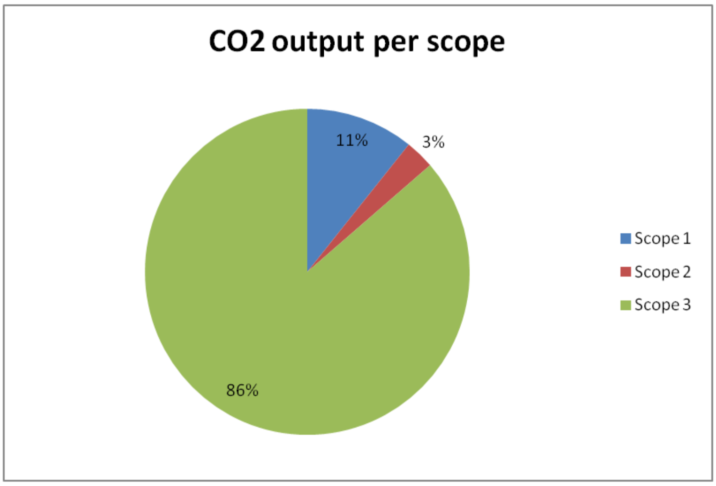


Energy emission and CO_2 emission per element (Cat V)

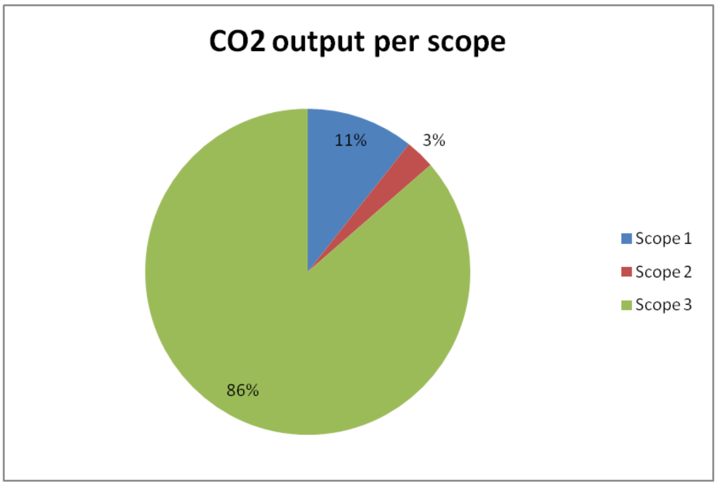
APPENDIX Z : DISTRIBUTION OF CO_2 OVER DIFFERENT SCOPES



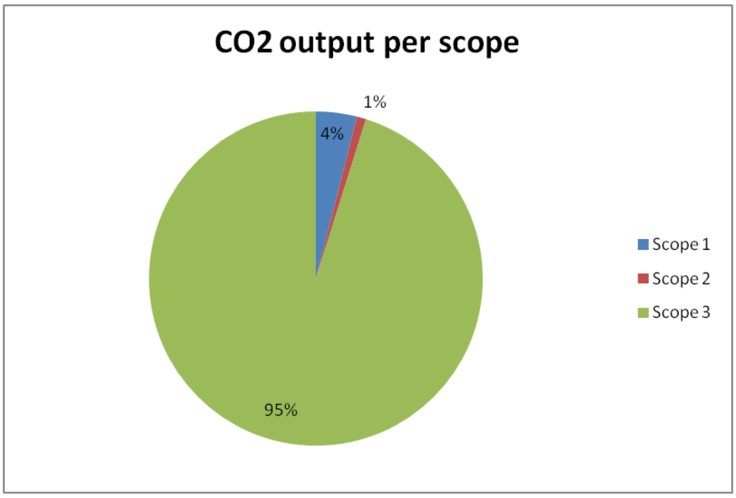
Emission of CO_2 per scope (Cat I)



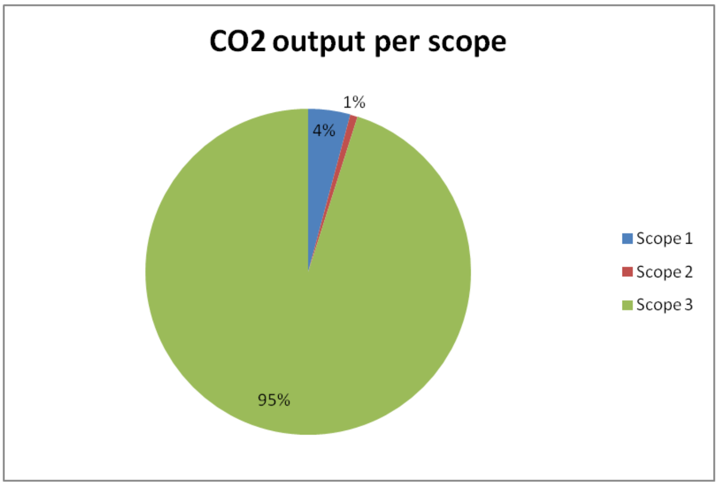
Emission of CO_2 per scope (Cat II)



Emission of CO_2 per scope (Cat III)



Emission of CO_2 per scope (Cat IV)



Emission of CO_2 per scope (Cat V)

APPENDIX AA : SENSITIVITY ANALYSIS (DETAILED)

Influence of reducing cement

Construction materials have a great contribution to the CO_2 emissions of a total project. From all construction materials the greatest contributor to the emissions of CO_2 is cement. Table AA.1 shows the reduction in emission of construction materials is cement would be reduced with 25%. Up to 15% of emissions of construction material can be reduced when using less cement in structures.

	Test case (kg CO2)	-25% cement (kg CO2)	Similarity
Cat I	180.000	157.000	87%
Cat II	180.000	157.000	87%
Cat III	180.000	157.000	87%
Cat IV	201.000	171.000	85%
Cat V	145.000	125.000	86%

Table AA.1: Comparison of emissions of construction material if cement is reduced by 25%

The sensitivity analysis is executed with a reduction of 25% of cement. As mentioned in the interviews with prefab production companies (see Appendix D and Appendix M) there are possibilities to reduce the quantity of cement in the concrete mixture. Whether or not a reduction of 25% of cement is possible depends on two factors: 1: structural feasibility and 2: legal feasibility. Important is that the structure is still save with less cement. Prefab companies have already mentioned they want to reduce cement in concrete mixtures but law prevent this.

Influence of reducing reinforcement

Reinforcement is besides cement the other big contributor to CO_2 emissions of construction material. Table AA.2 shows that up to 9% reductions on CO_2 emissions is possible in the emissions of construction material. In the construction of prefab "off the shelf" the reduction is 7%.

	Test case (kg CO2)	-25% reinforcement (kg CO2)	Similarity
Cat I	180.000	164.000	91%
Cat II	180.000	164.000	91%
Cat III	180.000	164.000	91%
Cat IV	201.000	186.000	93%
Cat V	145.000	132.000	91%

Table AA.2: Comparison of emissions of construction material if reinforcement is reduced by 25%

The same feasibility problems occur as with cement. Whether or not it is possible to reduce 25% of the reinforcement are both a structural and a legal matter. The result from the sensitivity analysis of reinforcement and cement shows that optimization of both construction materials could play an important role in reducing CO_2.

Influence of green energy

Acquiring and maintaining an environmental friendly image is a key focus point of many companies. A popular way to improve a company's image is the use green energy. This paragraph discusses the impact of the implementation of green electricity on a project. All comparisons are made to the previous discussed worst-case scenario. It is important to remember that the model does not incorporate values regarding the electricity usage during the production of cement and reinforcement. The number of different production processes is too large and therefore a reliable figure on electricity usage is hard to obtain.

This Appendix discusses the possible reduction on a specific element, unless this is specifically stated differently; the influence on a total project is discussed in chapter 9.

Onsite

Construction companies focus primarily on their emissions. The influence of construction companies using green electricity is analyzed first. An overview of the total reductions in CO_2 emissions is given in Table AA.3. Construction methods which perform most of their activities onsite profit more from green electricity than prefab construction methods. NUON emits 610 g CO_2/kWh and hydroelectric power (water) emits 15 g CO_2/kWh. The difference between the two emission factors is a factor 41.

	Onsite		
	NUON (kg CO2)	Water (with SMK) (kg CO2)	Similarity
Cat I	29.000	22.000	77%
Cat II	27.000	21.000	76%
Cat III	28.000	21.000	76%
Cat IV	10.000	8.000	83%
Cat V	7.000	5.000	80%

Table AA.3: Comparison of CO2 emission of different energy suppliers (onsite)

Concrete factory

It is assumed that mixing concrete has the same emissions for each m^3 produced concrete, therefore there are no considerate differences expected between the variants. Concrete factories do not contribute much to the total CO_2 emission of a project. Table AA.4 displays far less impact of green electricity than would be expected, because foundation piles are produced in a prefab factory and the energy requirements of the prefab factory are more considerable. The reason Cat IV and Cat V are unchanged is because they produce their own concrete and have therefore no benefits of the usage of green energy.

	Concrete factory		
	NUON (kg CO2)	Water (with SMK) (kg CO2)	Similarity
Cat I	4.400	3.900	88%
Cat II	4.400	3.900	88%
Cat III	4.400	3.900	88%
Cat IV	14.800	14.800	100%
Cat V	8.600	8.600	100%

Table AA.4: Comparison of CO2 emission of different electricity suppliers (in concrete factory)

Prefab factory

When electricity in the prefab factory is substituted for green electricity this influences all construction methods because all use prefab foundation piles (Table AA.5). Cat IV and Cat V profit more from the introduction of green electricity. The electricity is required to light up the factory and keep the machines going. Unlike activities onsite, in a factory, most of the machines use electricity. A (prefab) factory can therefore have considerable benefits from switching to green electricity. The emissions of a project are more influenced by the emissions of the prefab factory than the emissions of the concrete factory.

	Prefab factory		
	NUON (kg CO2)	Water (with SMK) (kg CO2)	Similarity
Cat I	4.400	1.900	44%
Cat II	4.400	1.900	44%
Cat III	4.400	1.900	44%
Cat IV	14.800	5.400	37%
Cat V	8.600	3.100	36%

Table AA.5: Comparison of CO2 emission of different energy suppliers (in prefab factory)

Total

As concluded earlier the total quantity of emissions of Cat I- Cat IV are very much alike. The benefits of using green electricity are more or less similar. The most important conclusion from this paragraph is that there are improvements made when using green energy in all sectors; this benefits every construction method (up to 4%). The construction of insitu structures takes more time and therefore the emissions of the site office are larger. Implementing green electricity reduces these emissions (Table AA.6).

	Total project		
	NUON (kg CO2)	Water (with SMK) (kg CO2)	Similarity
Cat I	230.329	220.576	95,8%
Cat II	228.442	218.957	95,8%
Cat III	228.367	218.833	95,8%
Cat IV	256.698	245.721	95,7%
Cat V	179.503	172.700	96,2%

Table AA.6: Comparison of CO_2 emission of different energy suppliers (on total project)

On an element level, other conclusions are drawn. Focussing on a single element (take an abutment for example), the reductions obtained by constructing in prefab are larger. Table AA.7 shows a comparison made between the total emissions in the construction of an abutment. Almost no gain is acquired from constructing with green electricity in Cat I but in Cat V big reductions are achieved. The origin of this difference lies in the production process. Prefab construction is based more on electricity than insitu construction. Insitu construction uses more diesel in the process.

	Abutment		
	NUON (kg CO2)	Water (with SMK) (kg CO2)	Similarity
Worst case	30.000		
Cat I	29.900	29.800	100%
Cat V	25.600	24.600	96%

Table AA.7: Overview of emissions in abutments with the implementation of green electricity

Concluded from the implementation of green electricity can therefore be that insitu and prefab profit about the same from the implementation of green electricity. The only difference is the sectors where these gains are made.

Weight reduction

In chapter 8 there is already mentioned that reducing the weight of the structure influences the quantity of CO_2 emitted and energy consumed during the project. Reducing the weight of the structure reduces the size of the load bearing elements that are supporting it. This reduction works on to the foundation, which can also be designed lighter. These lighter elements affect the number of transports and the quantity of concrete that needs to be produced and the energy which is required onsite.

On columns

The QST discusses two types of decks, the solid flat slab and the deck composed of box beams. Weight reduction of a box beam has its effects on the size of the columns which support it. The deck, in the assumed case, weighs 972 ton when constructed as a solid flat bed, with box beams it weighs 654 ton. This is a weight reduction of 33%. Because there are more loads that affect the size of the columns (the forces of the traffic) there is a reduction of 25% on the size of the columns.

	MJ (solid)	MJ (Box beam)	Similarity	kgCO2 (Solid)	kgCO2 (Box beam)	Similarity
Material	28.000	21.000	75%	3.100	2.300	75%
Transport	4.000	3.000	85%	300	200	79%
Factory	0	0	76%	0	0	77%
Onsite	15.000	13.000	88%	1.200	1.000	88%
Total	46.000	37.000	80%	4.600	3.600	79%

Table AA.8: Comparison between energy consumption and CO2 emissions of columns (Cat I) with a solid deck and box beam deck

Table AA.8 compares the emissions of a column constructed insitu (Cat I), with a solid flat slab and a box beam deck. The results show that there is a relation between the quantity of concrete that is poured and the quantity of CO_2 emissions and energy consumption. A reduction of about 20% in both energy and CO_2 can be obtained in the emission of a column using the same construction technique but a lighter deck.

On abutments

The same influence the deck construction has on the columns it has on the abutments. Table AA.9shows the influence of the type of deck construction has on the abutments. The results are comparable to the emissions of the columns, a reduction of about 20% is possible on the emissions of a column with a different deck construction. The comparison shows that there is not an equal effect on the emissions per phase. The emissions in the factory and of the material are almost linear with the weight reduction. The emission in transport and onsite are not; because the reductions in the size of the elements influence some of the work onsite and of transport, but not all of it.

	MJ (Solid)	MJ (Box beam)	Similarity	kgCO2 (Solid)	kgCO2 (Box beam)	Similarity
Material	196.000	148.000	75%	21.900	16.500	75%
Transport	20.000	16.000	81%	1.600	1.300	81%
Factory	1.000	0	75%	100	100	75%
Onsite	78.000	73.000	93%	6.300	5.900	93%
Total	295.000	237.000	81%	29.900	23.800	79%

Table AA.9: Comparison between energy consumption and CO_2 emissions of abutments (Cat I) with a solid deck and box beam deck

On foundation

The influence of the deck on the emissions of the foundation is discussed.

	MJ (Solid)	MJ (Box beam)	Similarity	kgCO2 (Solid)	kgCO2 (Box beam)	Similarity
Material	497.000	374.000	75%	60.000	44.800	75%
Transport	106.000	76.000	72%	8.500	6.100	72%
Factory	38.000	26.000	69%	3.900	2.700	69%
Onsite	46.000	32.000	69%	3.700	2.600	69%
Total	687.000	508.000	74%	76.100	56.200	74%

Table AA.10: Influence of weight reduction of box beam deck on the CO_2 emission and energy consumption of the foundation

Table AA.10 shows constructing a deck with box beam girders instead a solid flat slab, results in a reduction of 26% on the CO_2 emission and energy consumption of the foundation.

The emissions of a total project are reduces emissions with 18% when constructing a box beam deck. 48% of this reduction is due to lighter foundation.

Influence of high strength concrete

The influence of the weight reduction is significant, as has been showed in the previous paragraph. This paragraph discusses the influence of high strength concrete on the prefab production process. It is the assumed that all the prefab elements are constructed with the same concrete as is used onsite (C35/C45). Table AA.11 displays the differences between the normal concrete and high strength concrete (HSC). The numbers given are a comparison between the emissions of a prefab construction with a solid deck with and without high strength concrete. It is assumed that the foundation piles are still constructed with C53/C65.

	Solid Deck		
	With HSC	Without HSC	Similarity
Material	201.000	180.000	90%
Transport	32.000	34.000	106%
Factory	15.000	16.000	106%
Onsite	10.000	10.000	102%
Total	257.000	239.000	93%

Table AA.11: Comparison between usage of HSC or not (in kg CO_2) on emission of total project

It is remarkable to see that the reductions in emissions made in transport, factory and onsite when constructing with high strength concrete do not weigh up to the increase in emissions from the production of material. When these numbers are researched further, it shows that the usage of high strength concrete is only in one situation not beneficial, as showed in Table AA.12. The difference between the deck on one side and the column, abutment and foundation on the other side occurs because the calculations of the columns and abutments assume that the usage of high strength concrete provides a weight reduction. In the calculations of the deck, the quantity of reinforcement is leading. This results in that the calculations of the deck the only difference in the quantity of CO_2 that is released lies in the type of concrete used. With the other elements there is also a change in material, transport and factory. Whether this assumption (about the quantity of concrete stays the same in decks) is correct is something that needs to be researched further. If this is not the case, it could be concluded that it is beneficial to use high strength concrete over normal (C35/C45) concrete because of the reduction in material, transport and in the factory. In Table AA.12 the comparison with construction with Cat I is made to display that the prefab process is all elements more efficient than insitu except for the construction of a deck.

	Cat I	With HSC	Without HSC
Deck/beam	112.000	152.000	126.000
Column	5.000	4.000	4.000
Abutments	30.000	26.000	30.000
Foundation	76.000	73.000	76.000

Table AA.12: Comparison of emissions (kg CO_2) between Cat I and Prefab (with and without the use of HSC)

The same results are expected with the implementation of insitu with HSC. When high strength concrete is used onsite. Considerable reductions are expected in the emissions of the construction material. More reductions although less considerable are expected in transport, factory and onsite. Constructing a deck with HSC is not expected to reduce emissions. It is important to realize that to use high strength concrete onsite additional preparations are needed to make sure the execution onsite is right. High strength concrete has a shorter hardening time, planning of the pours need to be exact to prevent extra costs and unused concrete.

Influence reduction project time

The project time depends on the total number of working-hours in the quick scan tool. If construction time would be reduced with 25%, the only the emissions of the site office would be affected by that. In Table AA.13 an overview is given of the emissions of the site office and when the construction time is shortened by 25%. In this comparison it is assumed that the efficiency of the project is not affected by the increase of implementation of equipment. The emissions of the site office are, beside the construction time, influenced by the type of electricity used by the construction company.

	Site office (kWh)	-25% Construction time
Cat I	11.300	8.400
Cat II	10.800	8.100
Cat III	10.900	8.200
Cat IV	2.700	2.000
Cat V	2.200	1.600

Table AA.13: Comparison of electricity required by site office if reduction of 25% in construction time

Influence electric or diesel crane

The choice between different types of cranes is important from a construction point of view. Diesel cranes are often preferred over (electric) tower cranes, because they are applicable in different situations. In the comparison it is assumed that there is only one type of crane onsite, either a diesel crane or tower crane. The comparison made in Table AA.14 is the sum of all the equipment used onsite per category. The comparison is between diesel cranes and tower cranes which run on grey electricity and green electricity. The reason that not all categories obtain the same quantity of reduction is to the number of operations onsite and which equipment is required for that operation. The generator that is used onsite for prestressing runs on diesel. Because the emissions onsite of Cat IV are relatively small, the influence of this generator is very noticeable, and the relative influence of the tower crane smaller.

	Diesel		Grey electricity		Green electricity		Diesel- grey		Diesel-green	
	MJ	kgCO2	MJ	kgCO2	MJ	kgCO2	MJ	kgCO2	MJ	kgCO2
Cat I	274.000	22.000	110.000	14.000	110.000	5.000	40%	62%	40%	22%
Cat II	255.000	21.000	105.000	13.000	105.000	5.000	41%	63%	41%	23%
Cat III	258.000	21.000	106.000	13.000	106.000	5.000	41%	63%	41%	23%
Cat IV	98.000	8.000	63.000	6.000	63.000	4.000	65%	78%	65%	54%
Cat V	65.000	5.000	39.000	4.000	39.000	2.000	59%	74%	59%	47%

Table AA.14: Overview of similarity in energy consumption and CO_2 emission (onsite) between diesel cranes and tower cranes

It is clear that reductions are to be obtained onsite, when electrical cranes are applied. Especially when combined with green electricity onsite. One of the biggest contributors to the onsite emission is the emissions of the cranes. Even though it is shown that reductions can be obtained by using tower cranes instead of diesel cranes, it is important to recognize that not everything is about numbers. When foremen prefer diesel cranes because they are better suited to do the job, this is a consideration which needs to be taken into account. If the people on the construction site are better motivated because the equipment onsite is better fitted to their needs, the production will increase and workers are happier. This is something which is hard to put into figures but is a factor which needs not to be underestimated. The appliance of tower cranes are especially used in small en compact construction sites. When construction sites get larger, tower cranes are less useful. With the construction of viaducts, tower cranes could be used; in other projects they might not be that useful.

Influence electricity onsite

Some construction sites have no electricity from the grid at their dispense. Electricity needed onsite needs to be generated via a (diesel) generator. In Table AA.15 the influence of that project characteristic is given. The table shows only the required electricity onsite, expressed in kg CO_2.

	Electricity (kgCO2)	No electricity (kgCO2)	Similarity
Cat I	29.100	31.500	108%
Cat II	27.400	29.600	108%
Cat III	27.700	29.900	108%
Cat IV	9.500	10.100	106%
Cat V	6.600	7.100	107%

Table AA.15: Comparison of CO_2 output between electricity available onsite or not

Table AA.15 shows that electricity onsite has a positive effect on the emissions of a project. The emissions onsite will increase with about 8% if there is no electricity onsite. Although this is a parameter often not controllable by the project team, it is important to incorporate this in the sensitivity analysis.

Influence transport distance raw material

The transport of raw material is a big contributor to the total amount of transport. The transport distance is reduced by 25%. This can be obtained by selecting different suppliers. From Table AA.16 it can be concluded that reducing the transport distance of raw material by 25% results in a reduction of up to 10% on the emissions of transport.

	Test case	-25% transport	Similarity
Cat I	17.000	16.000	91%
Cat II	17.000	15.000	91%
Cat III	17.000	15.000	90%
Cat IV	32.000	29.000	92%
Cat V	20.000	18.000	91%

Table AA.16: Influence on total amount of transport by reducing transport distance of raw material by 25%

Influence transport distance construction material

From the concrete factory and prefab factory the construction material needs to be transported to the construction site. Again the transport distance is reduced by 25%. Remarkable is that the influence of the reduction of transport of construction material is greater than the reduction of raw material to the factory. A reduction of up to 15% on the emission of transport can be obtained from reducing transport distance. From an environmental perspective it can therefore be a good idea to select suppliers close to the construction site.

Test case	-25% transport	Similarity
17.000	15.000	90%
17.000	15.000	88%
17.000	15.000	88%
32.000	27.000	85%
20.000	17.000	85%

Table AA.17: Influence of reduction of 25% on transport of construction material

Influence of transport distance of equipment and personal

It has already been showed that transport distance of raw material and construction material has considerable influence on the emission of a project. This paragraph discusses the influence the travel distance of personal and equipment has on the emission of a project. The distance is lowered by 25% in comparison of the test case.

Table AA.18 shows that reducing the transport distance of working personal and equipment has only a minor influence on the emission of the transport.

	Test case	-25% transport	Similarity
Cat I	17.000	17.000	96%
Cat II	17.000	16.000	97%
Cat III	17.000	16.000	96%
Cat IV	32.000	31.000	99%
Cat V	20.000	19.000	98%

Table AA.18: influence on emission of transport with reduction of 25% of the distance of personal and equipment

Influence hybrid cars

Companies are keen on giving their employees cars with green labels. This reduces the direct emissions of a company. The influence on the total project is discussed in this paragraph. Table AA.19 shows that a hybrid car will reduce the emissions of the transport up to 4%. Transport is only 10% of the total emissions. The influence of the implementation of hybrid cars is therefore not considerable.

	Average	Hybrid	Similarity
Cat I	17.100	16.500	96%
Cat V	19.600	19.400	99%

Table AA.19: Comparison of emission of between the use of hybrid and average cars (on total transport)

Influence of carpooling

Carpooling is a very popular way for construction companies to reduce emissions. In the test case which has been discussed it is assumed that workers to the construction site travel per 2 persons to the construction site. Because it is assumed that workers live closer to the factory than to the construction site, it is assumed that people who travel to the factory travel alone. When the labourers carpool with 4 people instead of 2 people the emissions decrease with about 4%, over the emissions in the total transport. Transport is only about 10% if the total emission. The initiative of carpooling with colleagues therefore seems to be a good idea, but in practise not much (environmental) gain is achieved by implementing it.

	2 persons/car	4 persons/car	
	kg CO2	kg CO2	Similarity
Cat I	17.100	16.000	96%
Cat V	19.600	19.000	99%

Table AA.20: Comparison of the total CO_2 emission between carpooling with 2 people and 4 people

Influence of size of the construction

Constructing a structure in a bigger size has influence on the emissions of the project. The influence of the emissions of the size of the construction is displayed in Table AA.21. All variables are kept the same, except the quantities of concrete. In this case the abutment is made twice as big. The values of the test case are multiplied with two to make a comparison. Table AA.21 shows that when an element becomes twice its size reductions occur in the emissions of the element, but only marginal; because most of the emissions are linear with the quantity of construction material. The reductions come from less transport and less work-hours onsite. The reductions with prefab are bigger because the emissions onsite depend on the number of elements that need to be placed. If less work-hours are required, the emissions of the site office will be lower. This is not incorporated in the table.

Overview Abutment	Test Case		Twice the quantity		Similarity	
	MJ	kgCO2	MJ	kgCO2	MJ	kg CO2
Worst-case	295.000	30.000	588.000	60.000	100%	100%
Cat I	295.000	30.000	588.000	60.000	100%	100%
Cat II	279.000	29.000	555.000	57.000	99%	100%
Cat III	281.000	29.000	553.000	57.000	98%	99%
Cat IV	232.000	26.000	444.000	50.000	96%	97%
Cat V	231.000	26.000	440.000	49.000	95%	97%

Table AA.21: Emissions of an abutment and if the structure is twice as big.

Influence of repetition on emissions

Some construction methods profit from repetition. In this case the number of abutments is doubled. This results in double the quantity of concrete and reinforcement. The results are shown in Table AA.22. The emissions are only from the abutment.

Overview Total	Test Case		Double the elements		Similarity	
	MJ	kgCO2	MJ	kgCO2	MJ	kg CO2
Worst-case	295.000	30.000	583.000	59.000	99%	99%
Cat I	295.000	30.000	583.000	59.000	99%	99%
Cat II	279.000	29.000	534.000	55.000	96%	97%
Cat III	281.000	29.000	533.000	55.000	95%	96%
Cat IV	232.000	26.000	464.000	51.000	100%	100%
Cat V	231.000	26.000	461.000	51.000	100%	100%

Table AA.22: Emission of abutment with twice the number of elements

It becomes clear that the largest reduction is obtained with insitu with standard formwork (Cat II). The formwork only has to be made once, after that, the formwork can be reused. Prefab (Cat V) has no gain of a bigger number of elements; because the prefab industry already profits from large scale production.

APPENDIX BB : DISTRUBUTION OF SENSITIVITY ANALYSIS OVER SCOPES

	Cat I			Cat V		
	Scope 1	Scope 2	Scope 3	Scope 1	Scope 2	Scope 3
Cement (-25%)			10%			11%
Reinforcement (-25%)			7%			7%
Green electricity (onsite)		3%			1%	
Green electricity (concrete factory)			0%			0%
Green electricity (prefab factory)			1%			3%
Weight reduction (box beam deck)			13%			16%
No high strength concrete			0%			-4%
Project time (-25%)		1%			0%	
Crane type	4%			1%		
No electricity onsite	-1%			0%		
Transport raw material (-25%)			1%			1%
Transport construction material (-25%)			1%			2%
Transport Equipment and personal (-25%)	0%		0%			
Hybrid cars	0%		0%			
Carpooling	0%		0%			
Total	3%	4%	33%	1%	1%	36%

APPENDIX CC : BIBLIOGRAPHY

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